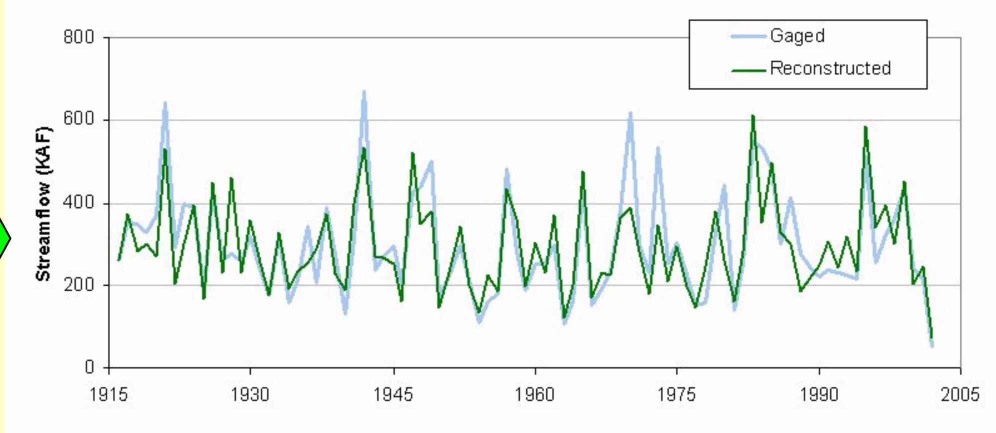
From Tree to Trace: How tree-ring reconstructions of streamflow are generated



Technical Workshop for Water Resource Managers

Connie Woodhouse and Jeff Lukas

NOAA-NCDC Paleoclimatology Branch and INSTAAR Dendrochronology Lab

NOAA

Western Water Assessment

INSTAAR University of Colorado Boulder

Welcome and Logistics

Plan for day
- series of informal presentations and demos
- drought planning and paleo
- several presentations from participants
- discussion

Morning and afternoon breaks

Lunch outside, take-out from Pei Wei

Parking in the garage

Introductions

Outline of workshop

- Introduction to dendrochronology, history, fundamentals
- Annual rings and crossdating [demo]
- How climate information is recorded in tree rings
- Site selection: maximizing the climate information in tree rings

BREAK

- Field and lab techniques
- Building a chronology from measured series
- The International Tree-Ring Data Bank [demo]

LUNCH

- Generating streamflow reconstructions from tree-ring data
  - Data selection and evaluation
  - Model selection, calibration and validation
  - Source of uncertainty in the reconstruction

BREAK

- Analyses of reconstructions; the 20th/21st centuries in perspective
- Relevance to a changing climate?
- Drought planning and paleoclimatology
- Applications to water resource management, open discussion

Acknowledgements

Workshop assistance:

ISPE – Gregg Garfin, Teresa Woolfenden

LTRR - Katie Hirschboeck, Dave Meko, Scott St. George, Erika Wise, Ellis Margolis, Rex Adams

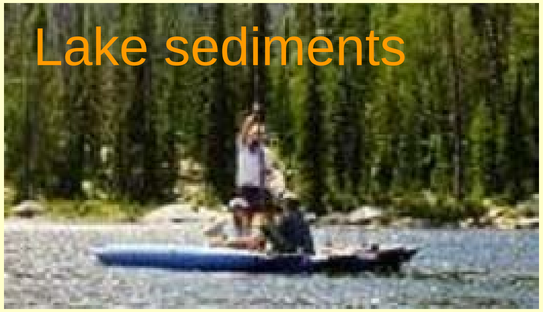
Partners and Collaborators:

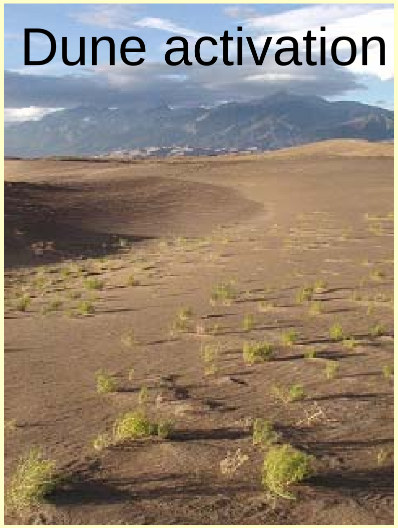
Denver Water, Hydrosphere Resource Consultants, Northern Colorado Water Conservancy District, Rio Grande Water Conservation District, CA Dept Water Resources, US Bureau of Reclamation, US Geological Survey, City of Westminster, Wright Water Engineering

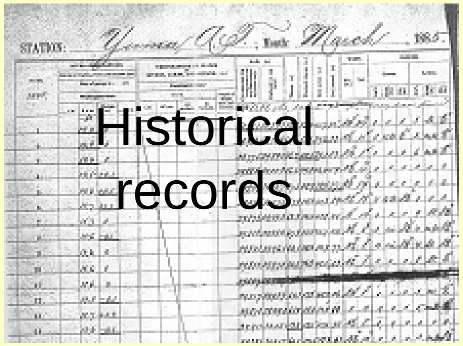
Funding:

NOAA Office of Climate Programs: Western Water Assessment and Climate Change Data and Detection (GC02-046); Denver Water; USGS

What is Paleoclimatology?







Paleoclimatology reveals what has actually happened

Jonathan Overpeck

Key attributes of tree rings as a climate proxy

- Annual resolution
- Continuous records (100-10,000 yrs)
- High sensitivity and fidelity to climate variability
- Widespread distribution

Dendrochronology:

the science that deals with the dating and study of annual growth layers in wood

Fritts 1976

Dendrochronology

Dendroarchaeology

Dendroecology

Dendrogeomorphology

etc.

Dendroclimatology

The science that uses tree rings to study present climate and reconstruct past climate

Dendrohydrology

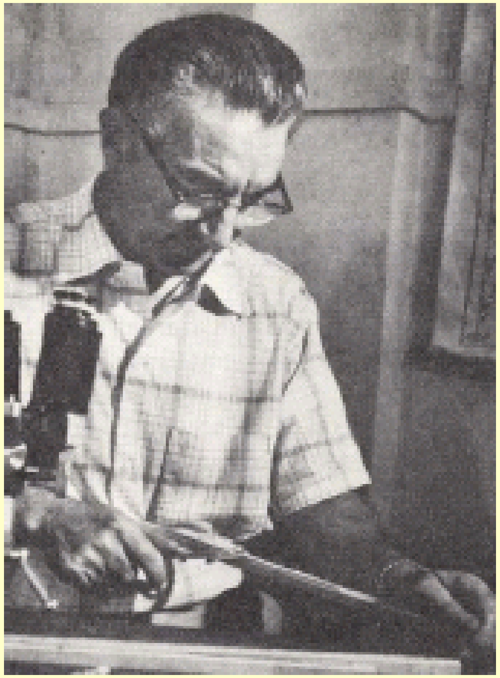
The science that uses tree rings to study changes in river flow, surface runoff, and lake levels

Key people and advances in dendrochronology, dendroclimatology, and dendrohydrology

- **A. E. Douglass - 1900s - 1950s**
  - "father" of modern tree-ring science
  - established crossdating as a rigorous methodology
  - used ring-width as proxy for climate variability

Key people and advances in dendrochronology, dendroclimatology, and dendrohydrology

- **Edmund Schulman - 1930s - 1950s**
  - extensive sampling across West for climate sensitivity
  - systematic examination of climate - growth relationships
  - discovered great age of bristlecone pine and other species
  - first dendrohydrologic studies of Colorado River basin



Key people and advances in dendrochronology, dendroclimatology, and dendrohydrology

- **Hal Fritts - 1960s - present**
  - physiological basis of ring width sensitivity to climate
  - modern statistical procedures for climate reconstruction
  - reconstruction of large-scale climate patterns
  - *Tree Rings and Climate* (1976)

Key people and advances in dendrochronology, dendroclimatology, and dendrohydrology

- **Ed Cook - 1980s - present**
  - program for chronology compilation (ARSTAN)
  - gridded drought (PDSI) reconstructions for N. America
- **Dave Meko - 1980s - present**
  - further development of statistical procedures for climate and streamflow reconstructions
  - streamflow reconstructions of Gila, Sacramento, Colorado, etc.

Principles of Dendrochronology

The Uniformitarian Principle

Principle of Limiting Factors

Principle of Crossdating

Principle of Site Selection

Principle of Replication

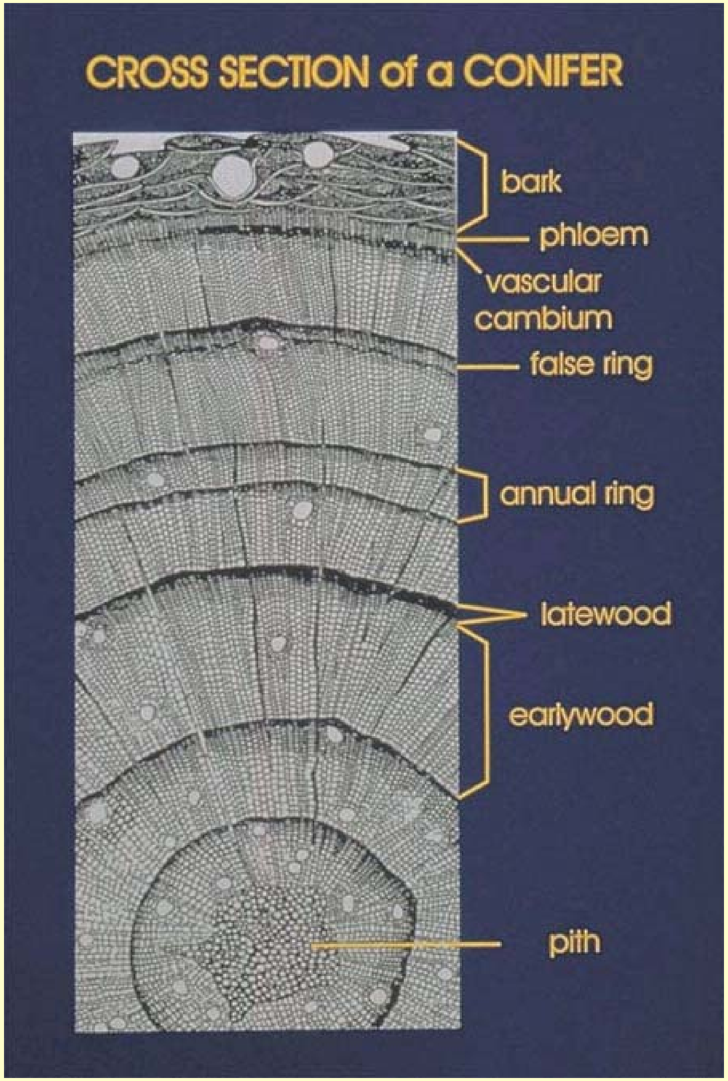
The Uniformitarian Principle

“The present is the key to the past”

- That is, the processes that were operating at some time in the past (e.g., those that govern the relationship between climate and tree growth) are the same as those operating today
- First proposed by Lyell in 1830s to explain origin of geologic features, it underpins all earth sciences, including dendrochronology

Annual Rings and the Principle of Crossdating

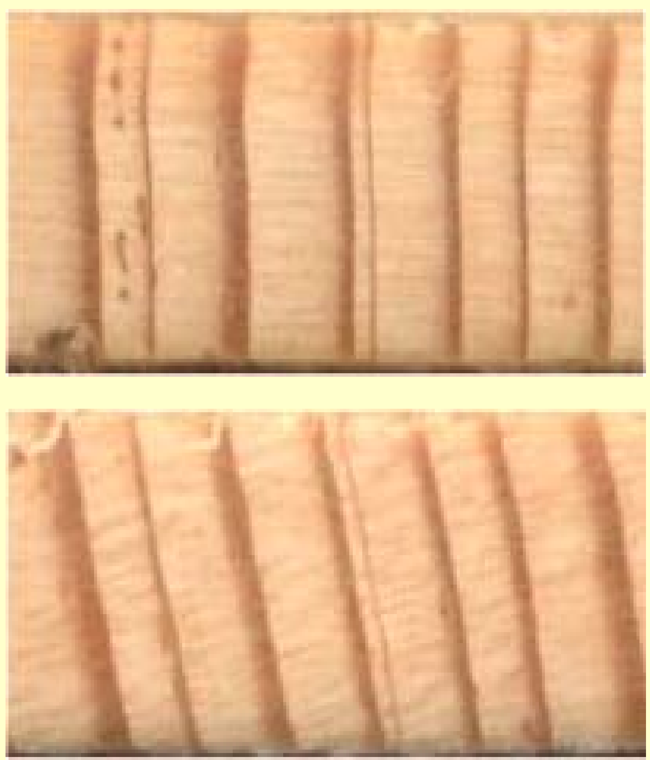
How annual growth rings form



- In temperate climates, one distinct growing season per year, so one growth ring = one *annual ring*
- New wood cells form in the cambium, underneath the bark
- *Earlywood* has large, thin-walled cells and appears light
- Towards the end of the growing season, cells are smaller and thick walled and appear darker: *latewood*
- Earlywood + latewood = growth ring
- *Note that rings have varying widths**

In regions where climate is the main control on growth, variations in ring width are common among trees

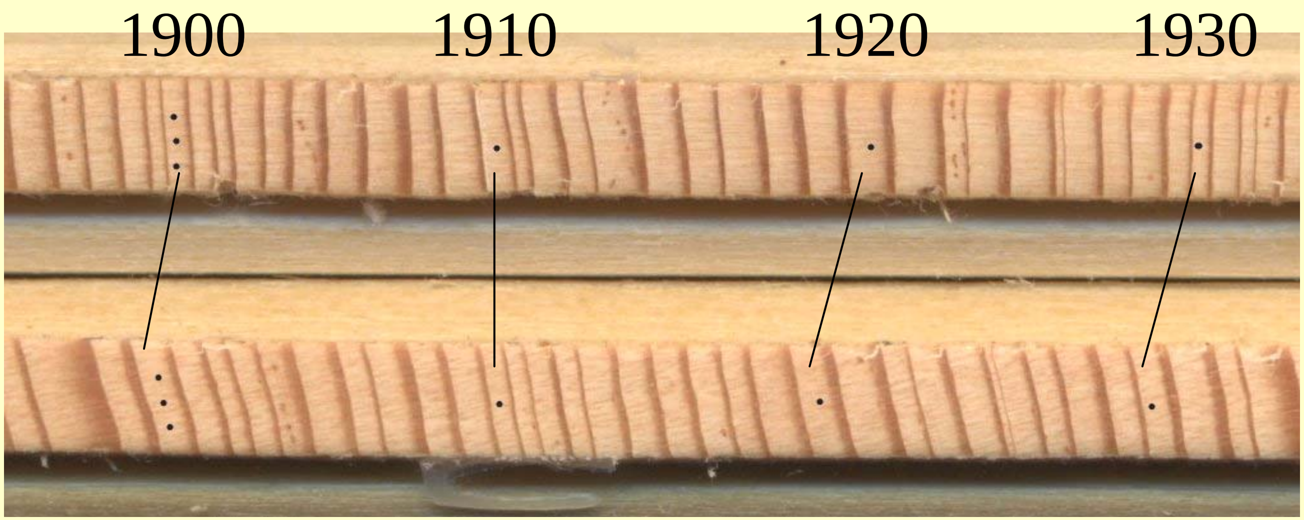
Since each tree in an area is experiencing the same climate, the pattern of wide and narrow rings is often *highly replicated* between trees



Portions of cores from 2 Douglas-fir trees at same site (Eldorado Canyon, CO)

Principle of Crossdating:

Matching the patterns in ring widths or other ring characteristics (such as frost rings) among several tree-ring series allows the identification of the exact year in which each tree ring was formed



Portions of cores from 2 Douglas-fir trees at same site (Eldorado Canyon, CO)

Regional climate patterns = regional crossdating

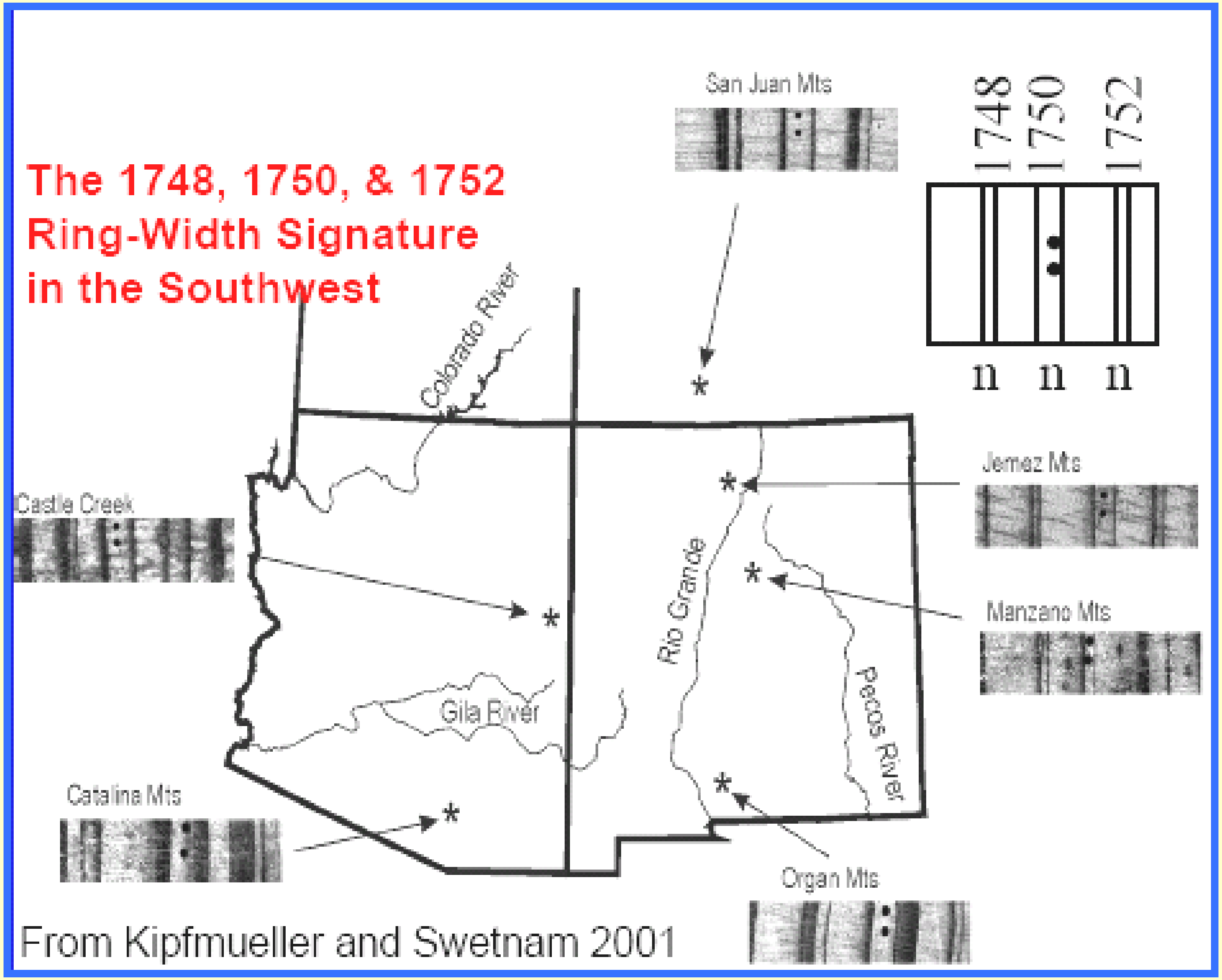
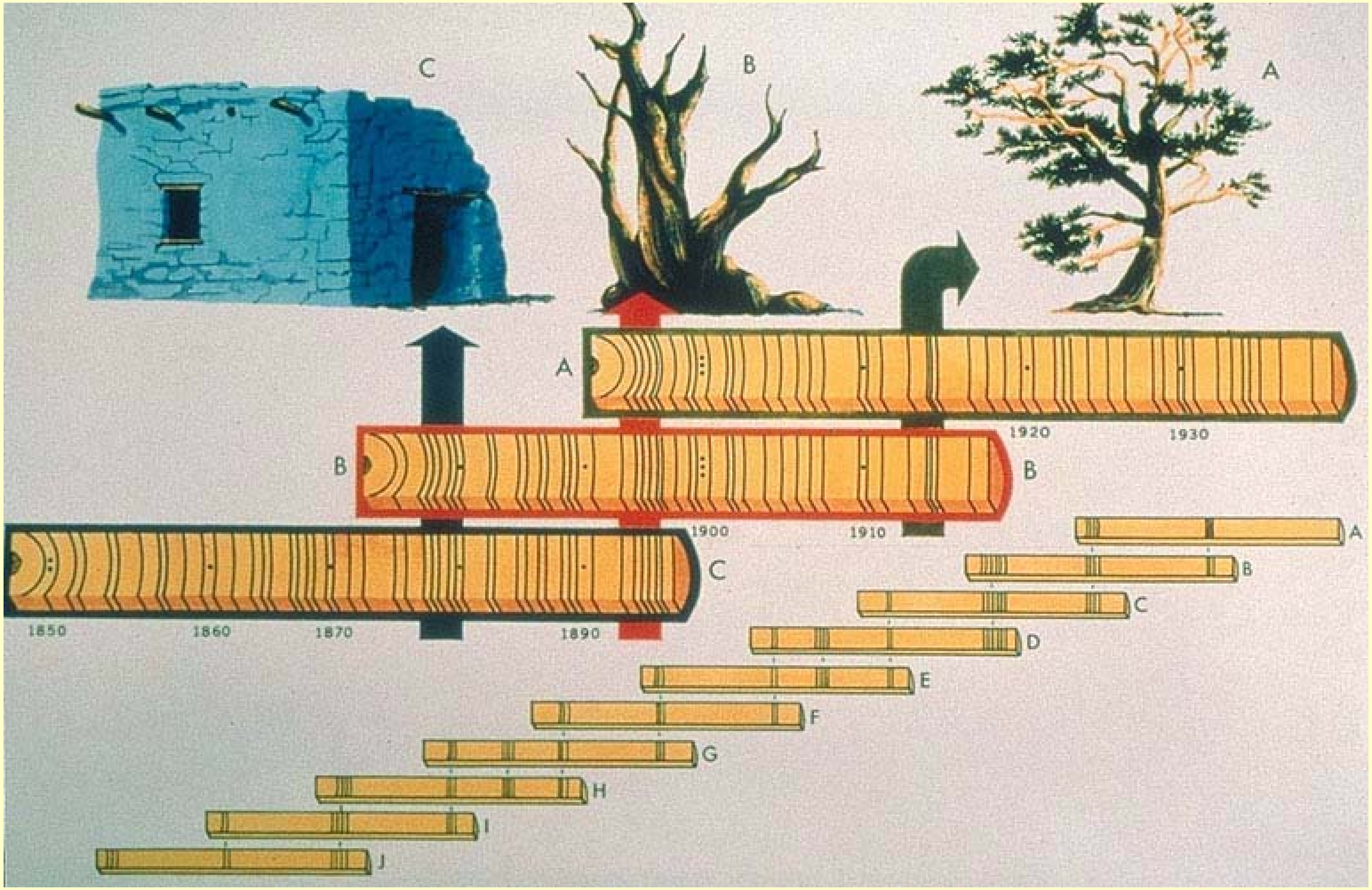


Image courtesy of K. Kipfmueller (U. MN) and T. Swetnam (U. AZ)

Crossdating allows the extension of tree-ring records back in time using living and dead wood



Core exercise

Image courtesy of LTRR (U. AZ)

Principle of Limiting Factors

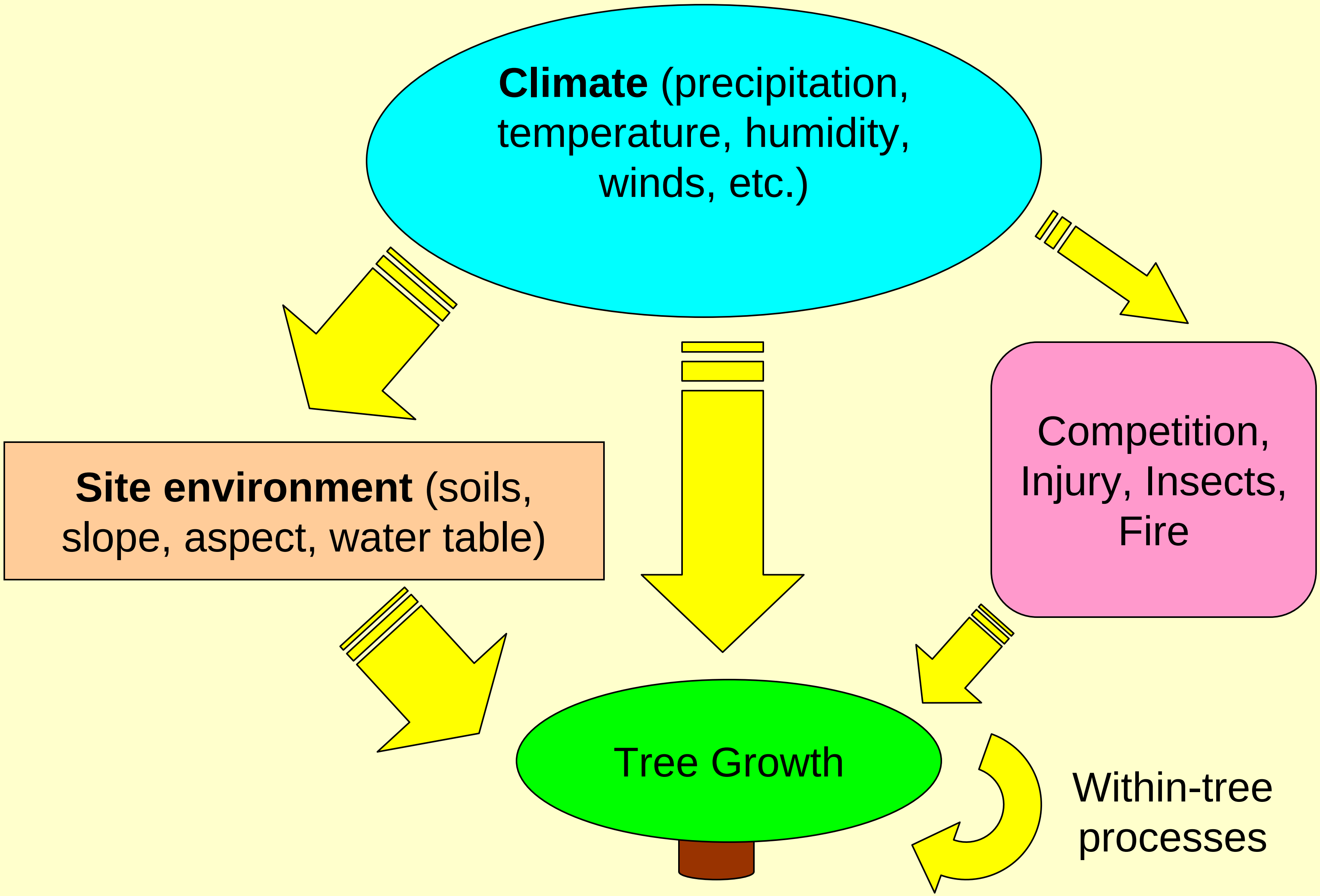
- A biological process (e.g., tree growth) cannot proceed faster than is allowed by its most limiting factor

Climate is typically the main limiting factor on tree growth in the West

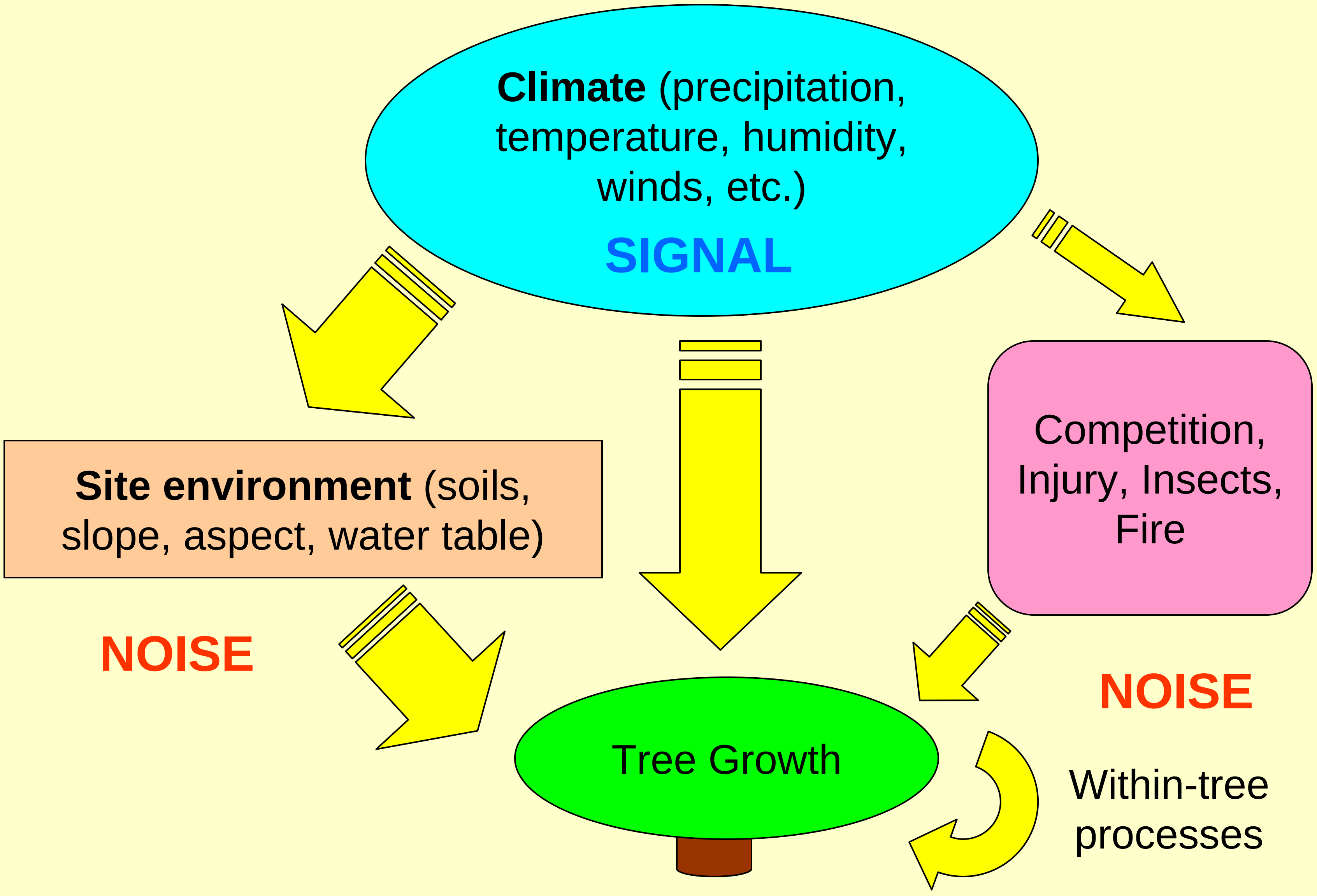
- At high elevations, growth is typically limited by summer warmth and length of the growing season

- At lower elevations, growth is typically limited by moisture availability

Climate is not the only *influence* on growth



The main goal is to increase Signal:Noise ratio



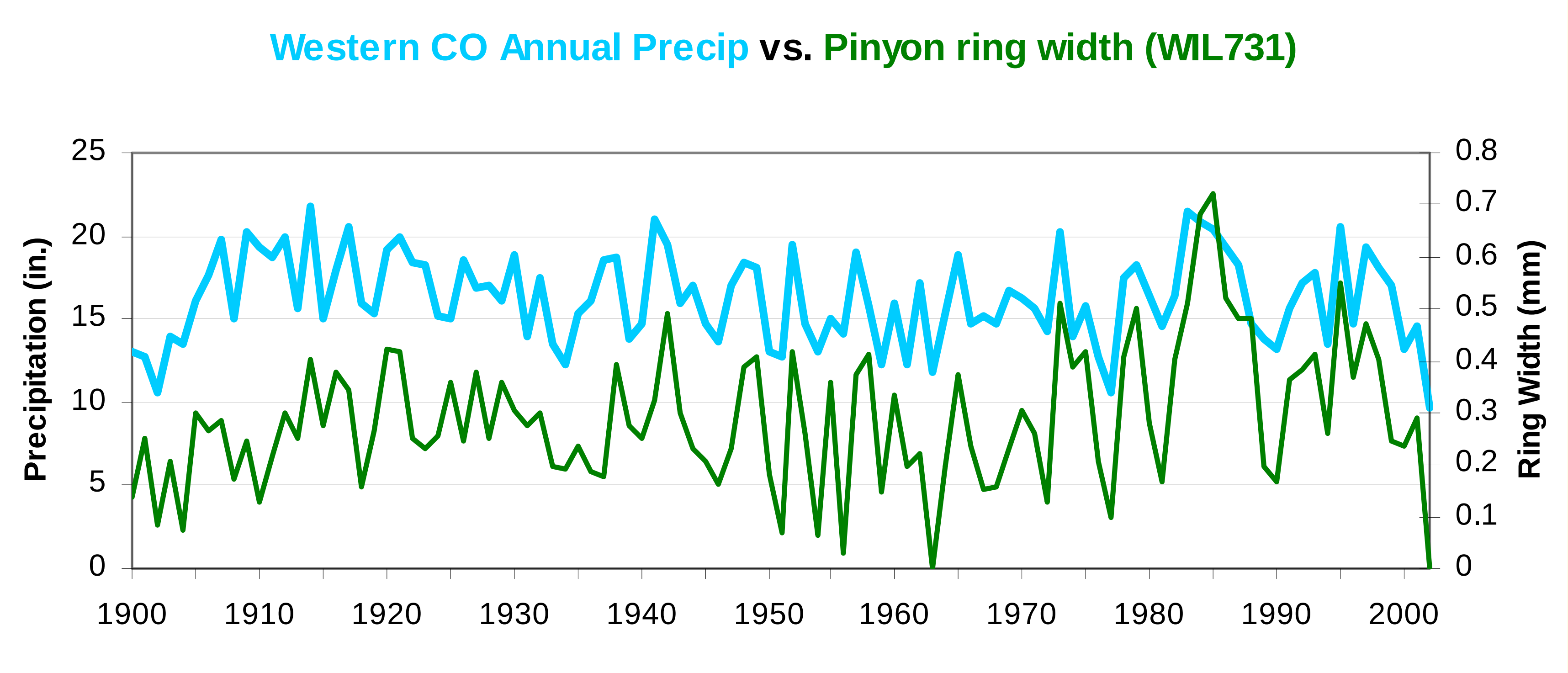
Moisture sensitivity

- “Moisture-sensitive” trees are ones whose year-to-year ring-width variability mainly reflects changes in moisture availability

- These changes are driven mainly by *precipitation*

- Temperature, humidity, and wind play lesser roles, by modifying *evapotranspiration* (moisture losses from soil and directly from tree)

Example of moisture signal as recorded by a single tree - western Colorado



- Here, the “raw” ring widths from one tree are closely correlated to the annual basin precipitation (r = 0.69).
- Our job is to *capture* and *enhance* the moisture signal, and reduce noise, through careful sampling and data processing

Example of moisture signal as recorded by a single tree - central Arizona

Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

This moisture signal can be a proxy for multiple moisture-related variables

- Annual or seasonal precipitation
- Drought indices (e.g., PDSI)
- Snow-water equivalent (SWE)
- Annual streamflow

These variables are closely correlated in this region, and trees whose ring widths are a good proxy for one tend to be good proxies for all of them

Ring-width and streamflow - an indirect but robust relationship

- Like ring width, streamflow integrates the effects of precipitation and evapotranspiration, as mediated by the soil

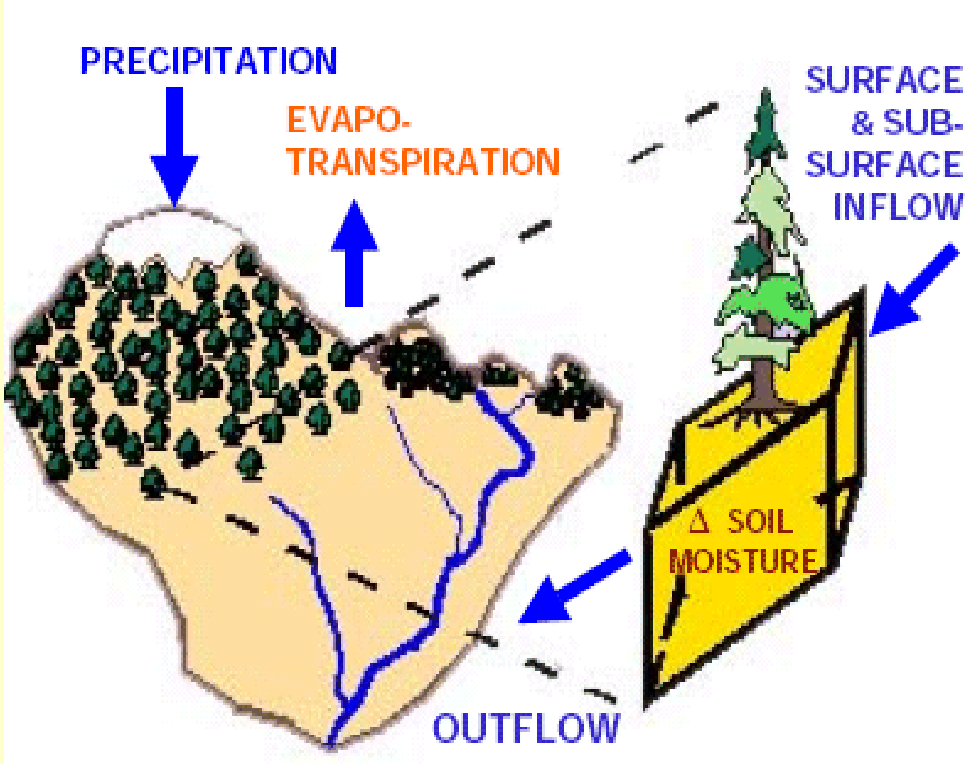


Image courtesy of D. Meko (U. AZ)

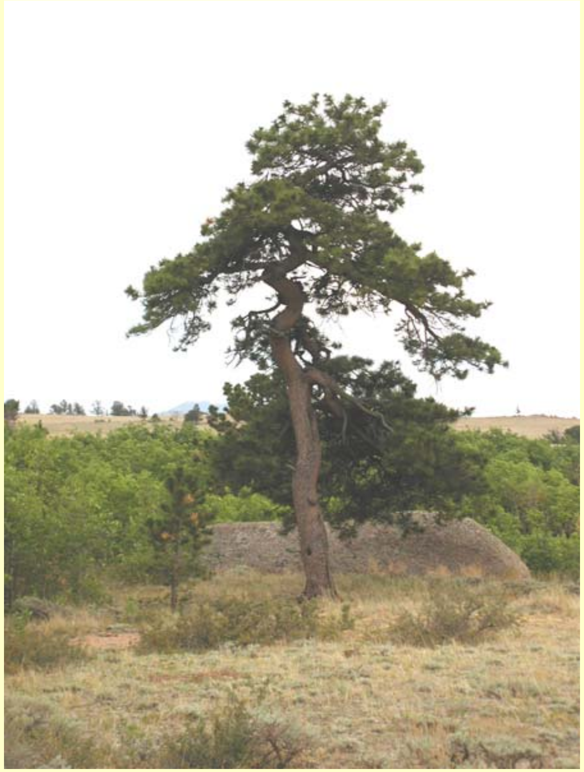
Principle of Site Selection

- Useful sites can be identified and selected based on criteria that will produce tree-ring series sensitive to the environmental variable being examined.
- Criteria for useful sites:
  - *species known to be moisture-sensitive*
  - *old trees (= long records)*
  - *lower portion of species' elevational range*
  - *site environment that induces moisture stress*

Principal moisture-sensitive species - CO, UT, AZ, NM

Douglas-fir
500-800 years

Pinyon Pine
500-800 years



Ponderosa Pine
300-600 years

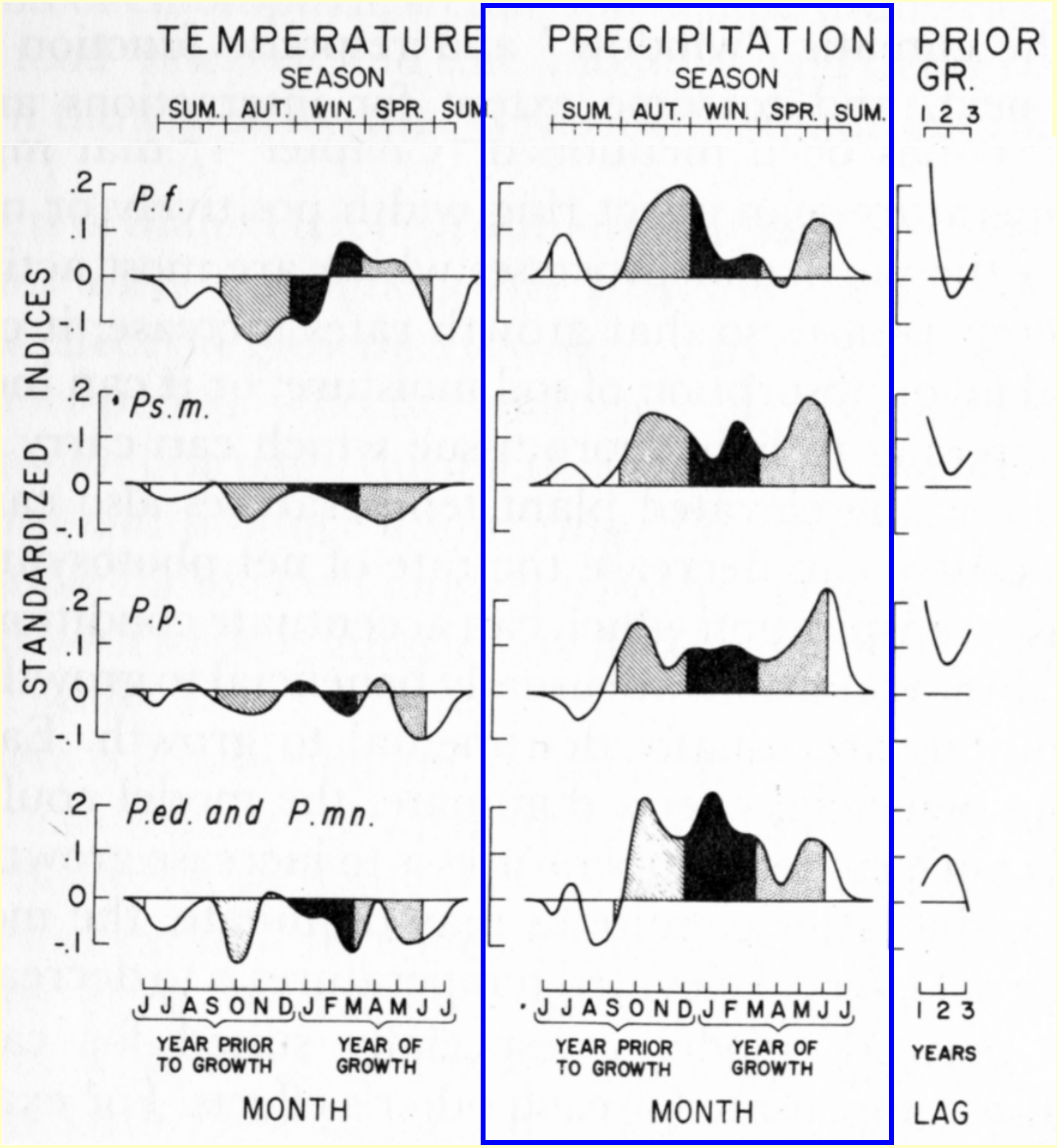
Climate responses by species - western US

Limber Pine

Douglas-fir

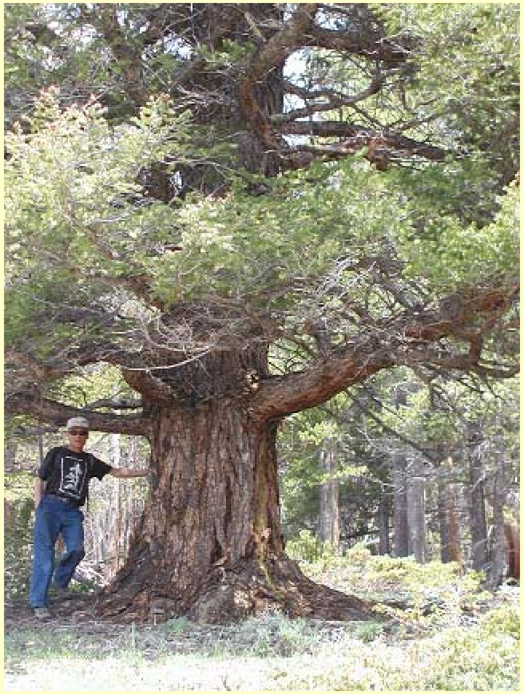
Ponderosa

Pinyon



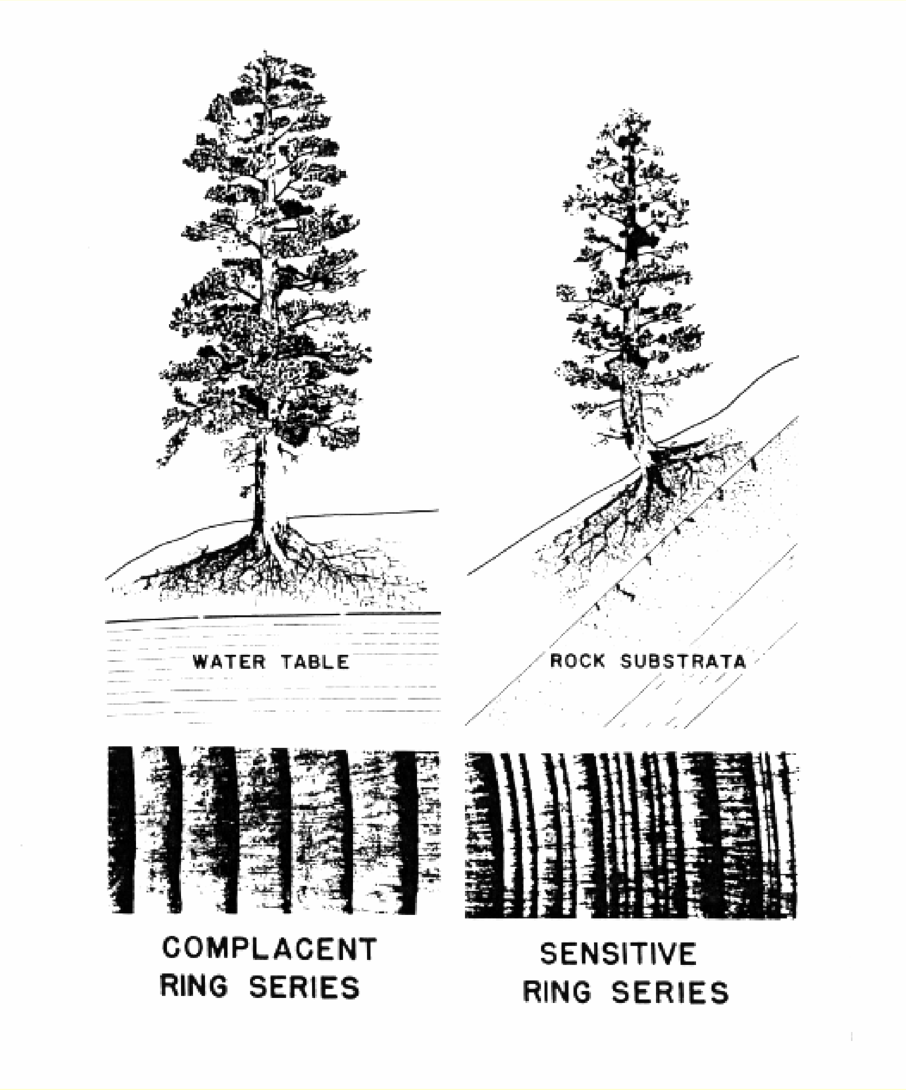
from *Fritts 1976*





Old tree characteristics: flat or spike tops, heavy and gnarled limbs, thick bark, large size*

Stressful sites produce ring series with greater sensitivity (higher Signal:Noise ratio)



from *Fritts 1976*

Characteristics of stressful sites

- Uplands, not near stream
  - well above water table
- Thin, rocky soils
  - low retention of soil moisture
- Steep slopes
  - low retention of soil moisture
- South- or west- facing
  - greater heating, more stress
- Low tree density
  - less noise from competition, fire, insects

Site selection to enhance the moisture signal

- *Is this a good site? Why or why not?*

- *What about this site?*

Site selection to enhance the moisture signal



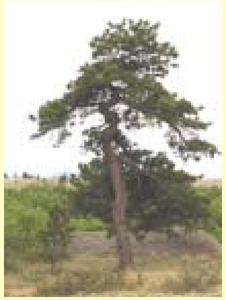
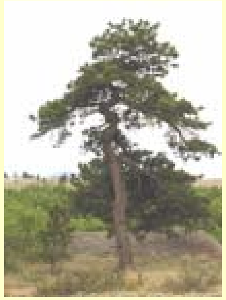
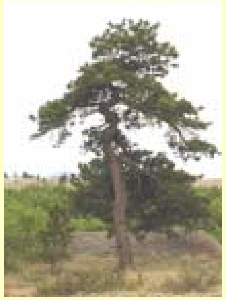
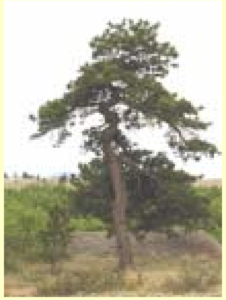
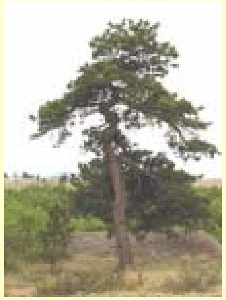
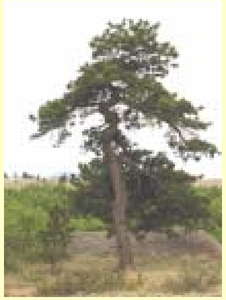


Building a Tree-Ring Chronology,

Part I

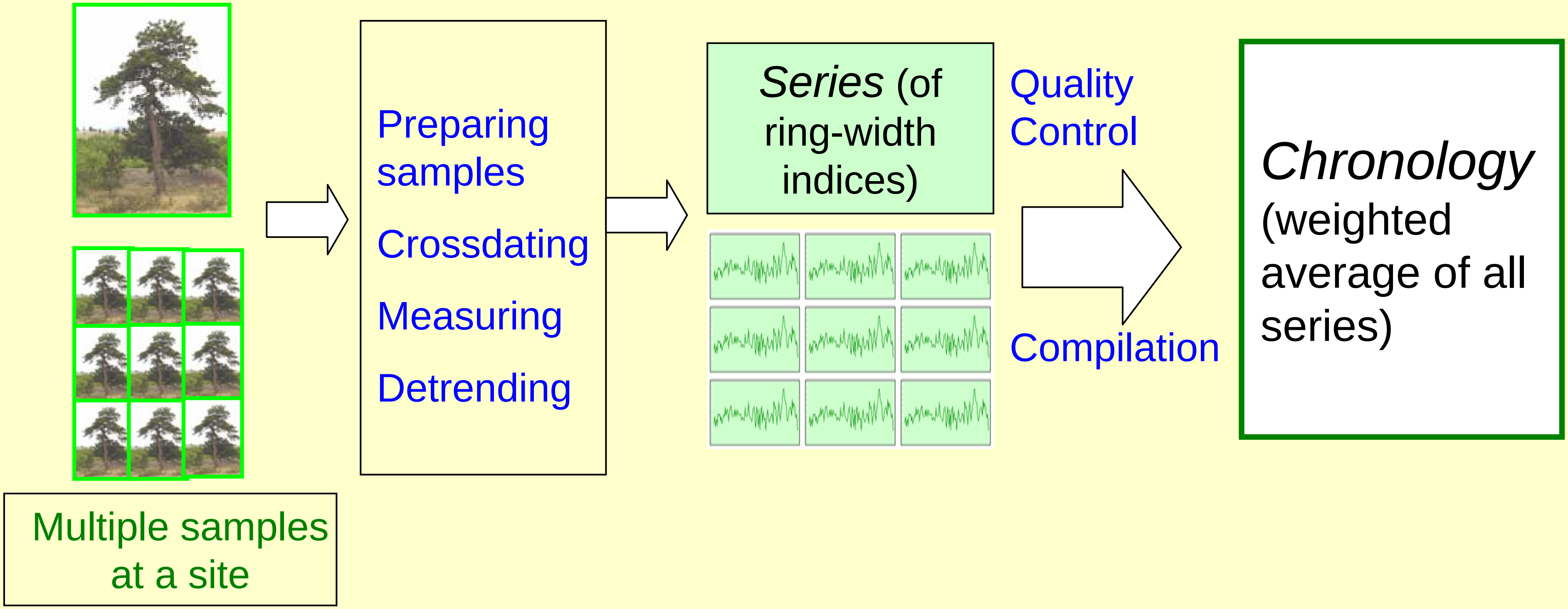
Field and Laboratory Techniques

Principle of Replication

- The environmental signal being investigated can be maximized, and the amount of "noise" minimized, by sampling more than one radius per tree and multiple trees per site
- The end-product of this sampling replication is the site **ring-width chronology**
- Chronologies are the “building blocks” of streamflow reconstructions

Steps in Building a Tree-Ring Chronology

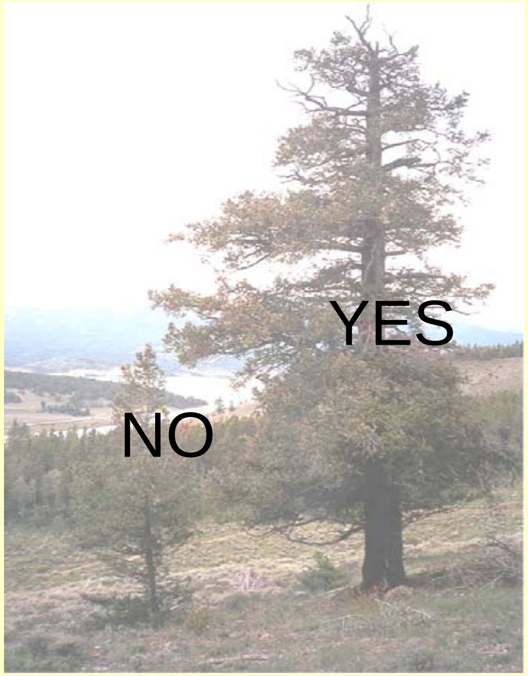


Sampling to develop a site chronology

- Sample 10-30 trees at a site, same species

- Select old-appearing trees

- Goal: maximize the sample depth throughout the chronology (300-800+ years)
  - chronology quality is a function of sample depth
  - depth always declines going back in time, since oldest trees are rarer



Sampling living trees

Image courtesy of K. Hirschboeck (U. AZ)

- Increment borer collects core 4-5mm in diameter, up to 20” long
- Causes minimal injury to the tree

Sampling dead trees ("remnant" wood)

- Increment borers can also be used to sample remnant wood (stumps, snags, logs)

- But it's often better to saw cross-sections

Sampling to develop a site chronology

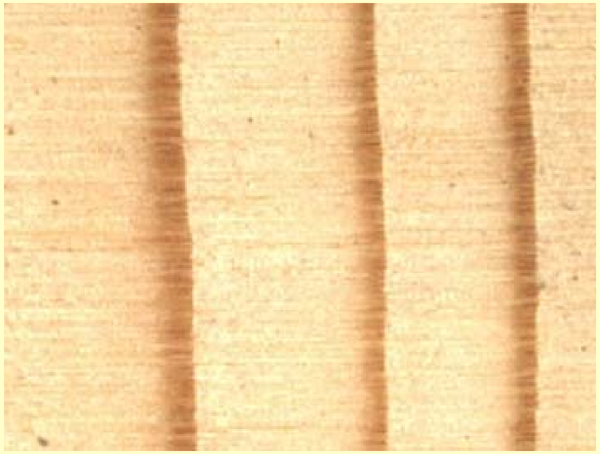
- Collect *two* cores (radii) from each tree, extending to the pith

- The two radii are from opposite sides of the tree
  - average out within-tree ring-width variability
  - facilitate identification of absent and micro rings

Schematic of coring for typical tree

Preparing the cores

- Cores are left to air dry for at least a few days, then glued to wooden core mounts



NO - can't see cells

- Cores are sanded with a belt sander, then hand-sanded to 1200-grit

OK - ready to crossdate

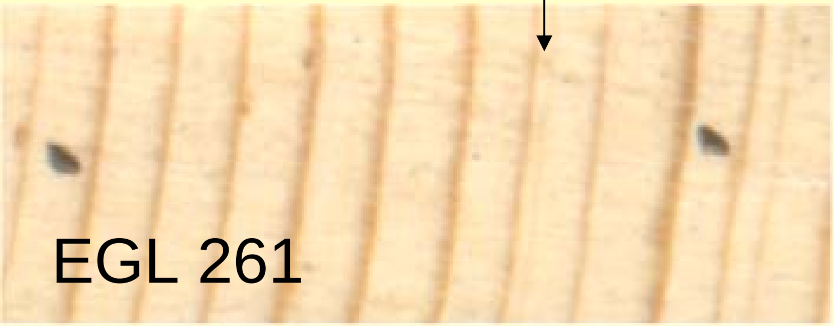
- Individual cells (tracheids) must be clearly visible

Cross-dating the cores

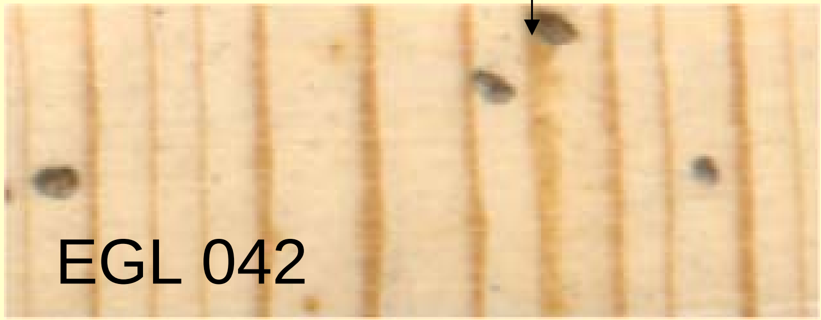
- Crossdating cores from living trees is usually straightforward, since the outside date is known

- Main challenge is inferring absent rings from pattern (mis)matches with other trees
  - frequency of absent rings ranges from 0 - 4% per site
  - cores with up to 10% absent rings can be crossdated

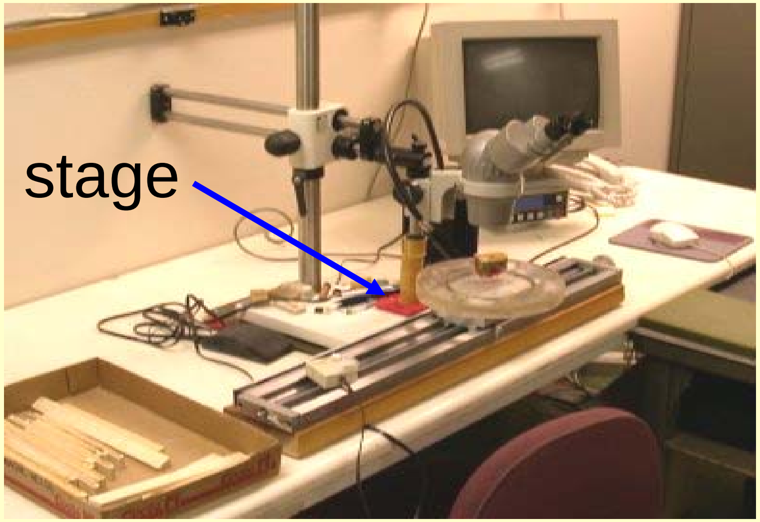
1977 present but very narrow

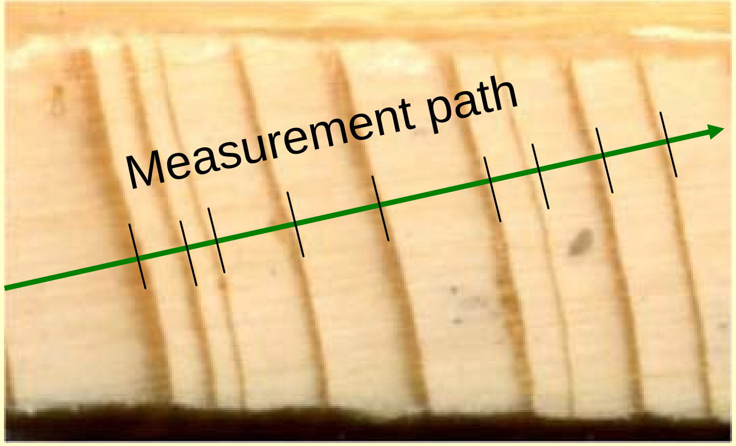


1977 inferred to be absent



Measuring the cores

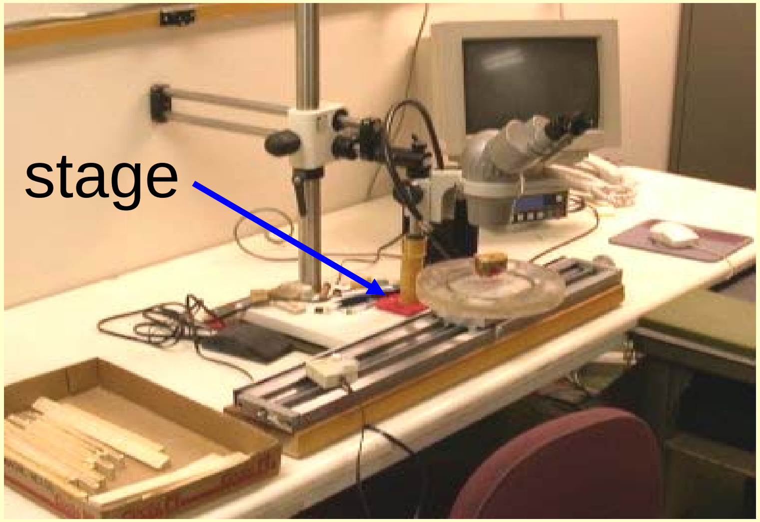


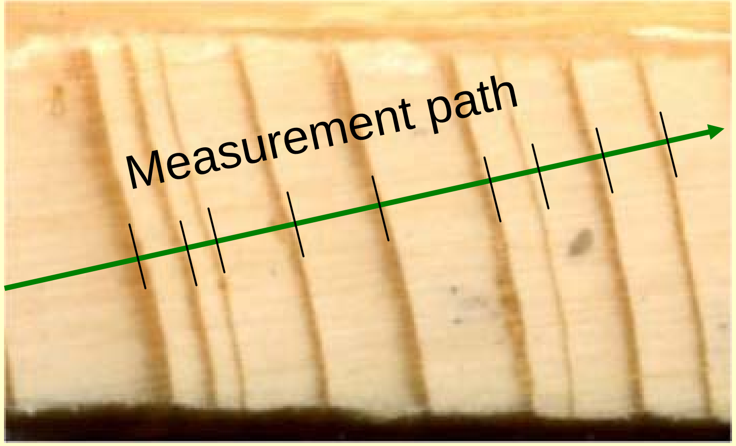


- Computer-assisted measurement system
  - turning knob advances the stage under the microscope
  - linear encoder captures position of core to nearest 0.001mm (1 micron)
  - actual precision is ~5 microns

- Measurement path is parallel to the rows of cells (and perpendicular to the ring boundaries)

Measuring the cores





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Sources of uncertainty

- measurement error
- ring-widths on core may not be representative of tree

Assessing the quality control of dated/measured series

- The program COFECHA runs correlations for each series with a master chronology derived from the other series
- Easy to identify the rare series that has been mis-dated or mis-measured or simply does not follow the common site signal

PART 5: CORRELATION OF SERIES BY SEGMENTS: vbu5 11:21 Fri 23 JUL 2004

Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1550 1599	1575 1624	1600 1649	1625 1674	1650 1699	1675 1724	1700 1749	1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	vbu032	1750 1985									.76	.80	.84	.89	.89	.82	.79	.86	.83	
2	vbu031	1763 2003									.71	.70	.71	.78	.81	.69	.67	.78	.73	.77
3	vbu041	1748 2003								.69	.70	.76	.80	.76	.80	.83	.75	.82	.75	.79
4	vbu042	1794 2003										.78	.77	.85	.81	.72	.78	.85	.77	.80
5	vbu051	1730 2003								.65	.70	.69	.75	.84	.85	.80	.78	.85	.85	.87
6	vbu052	1713 2003							.59	.64	.61	.70	.85	.88	.87	.85	.83	.84	.81	.83
7	vbu131	1640 1864				.86	.86	.87	.76	.79	.78	.68	.73	.84						
8	vbu142	1566 1796	.73	.77	.76	.76	.76	.67	.58	.67	.77									
9	vbu143	1566 1608	.60																	
10	vbu161	1740 2003								.61	.59	.64	.67	.84	.91	.86	.76	.71	.66	.67
11	vbu162	1739 2003								.60	.68	.65	.75	.85	.85	.76	.73	.77	.66	.71
12	vbu153	1704 1985							.72	.64	.63	.74	.80	.82	.87	.86	.84	.89	.83	
13	vbu121	1796 2003										.70	.71	.88	.93	.87	.82	.85	.83	.85
14	vbu172	1815 2003											.75	.78	.78	.73	.65	.78	.74	.76
15	vbu141	1666 1825					.73	.81	.71	.75	.80	.72	.72							
16	vbu151	1829 1942												.82	.87	.83	.74			
17	vbu181	1573 1694	.71	.71	.65	.73	.84													
18	vbu183	1573 1607	.66																	
19	vbu183	1615 1660			.64															
20	vbu011	1748 2003								.82	.83	.87	.82	.79	.80	.75	.74	.84	.79	.80
21	vbu012	1748 2003								.84	.85	.84	.82	.85	.86	.83	.82	.87	.84	.86
22	vbu021	1750 2003									.54	.66	.72	.79	.86	.85	.86	.89	.82	.84
23	vbu123	1621 1916			.71	.70	.83	.75	.64	.70	.78	.73	.72	.84	.89	.87				
24	vbu122	1621 2003			.70	.67	.80	.73	.69	.75	.71	.73	.79	.88	.93	.79	.73	.87	.82	.83
25	vbu111	1628 1692				.74	.73													
26	vbu152	1599 1980		.63	.62	.83	.75	.63	.65	.77	.80	.84	.86	.82	.80	.82	.85	.79	.76	
27	vbu132	1631 1737				.70	.77	.73	.66											
28	vbu171	1783 2003										.60	.72	.79	.72	.69	.71	.75	.80	.83
29	vbu201	1780 2003										.84	.85	.84	.78	.72	.80	.75	.72	.75
30	vbu202	1780 2003										.80	.77	.75	.81	.78	.79	.86	.89	.90

Typical COFECHA output, from VBU

1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
.89	.82	.79	.86	.83	
.81	.69	.67	.78	.73	.77
.80	.83	.75	.82	.75	.79
.81	.72	.78	.85	.77	.80
.85	.80	.78	.85	.85	.87
.87	.85	.83	.84	.81	.83

Using COFECHA for quality control

Seq	Series	Time_span		1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999
1	rpr051	1849	1920					.68	.78	.87			
2	rpr07	1854	1997						.83	.85	.89	.90	.86
3	rpr061	1745	1936	.23B	.26B	.26B	.18B	.48	.89	.93	.81		
4	rpr011	1860	1997						.65	.71	.83	.90	.86
5	rpr092	1864	1997						.70	.77	.71	.84	.88
6	rpr091	1878	1997							.74	.76	.87	.87
7	rpr061	1743	1997	.37B	.39B	.65B	.76	.81	.91	.92	.92	.90	.89
8	rpr081	1871	1997						.76	.78	.87	.80	.68
9	rpr052	1848	1997					.85	.85	.92	.89	.93	.93
10	rpr051	1848	1997					.88	.88	.91	.90	.92	.91

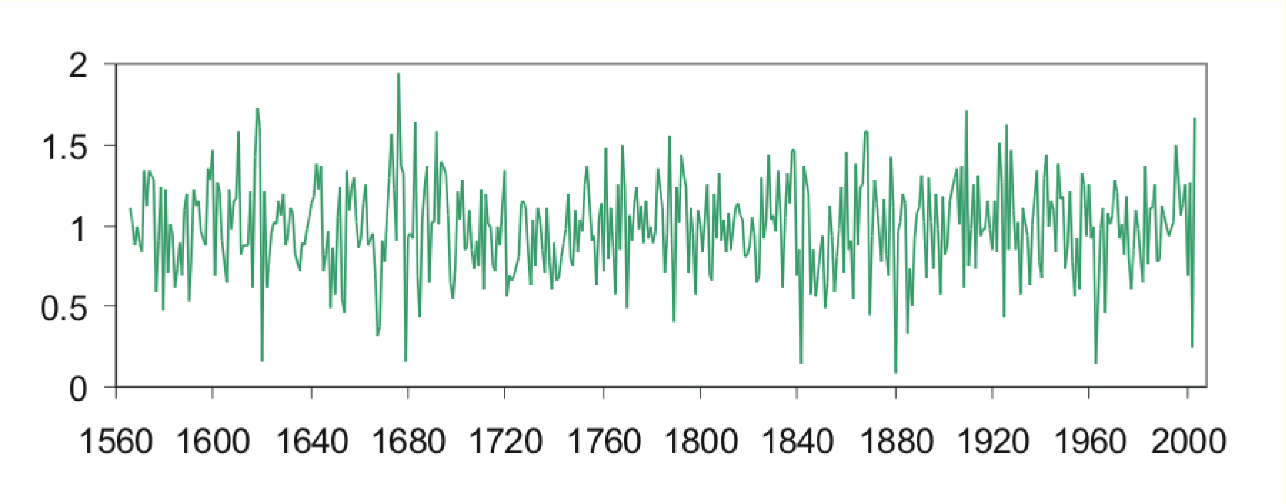
rpr061 1745 to 1936 192 years

[A] Segment	High	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	+0	+1	+2
1745 1794	-2	_	_	_	_	_	_	_	_	.88*	.14	.23	.12	_.03
1750 1799	-2	_	_	_	.05	_.10	_.06	.45	.09	.86*	.17	.26	.10	_.05
1775 1824	-2	_.15	_.21	_.40	_.14	_.28	.02	.40	.16	.80*	.27	.26	.10	_.18
1800 1849	-1	_.06	.03	_.22	_.41	_.15	.17	.01	.08	.10	.65*	.18	_.14	_.35

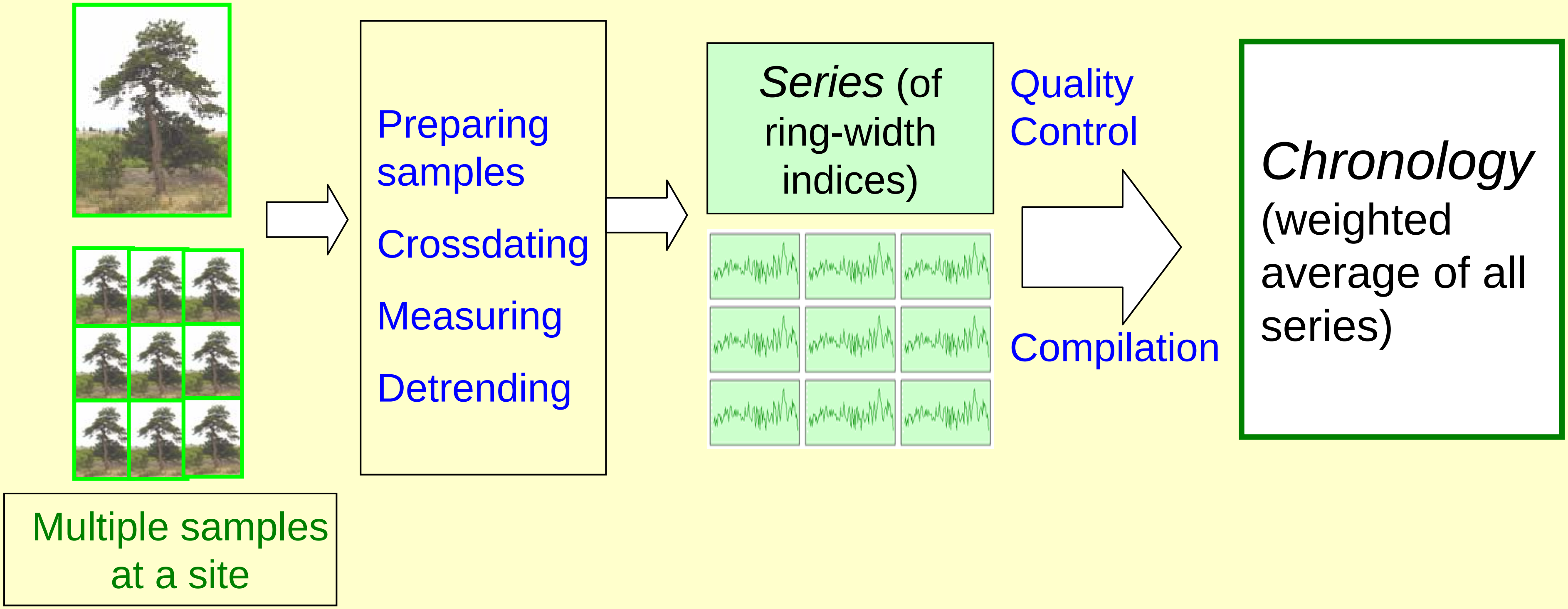
Building a Tree-Ring Chronology

Part II

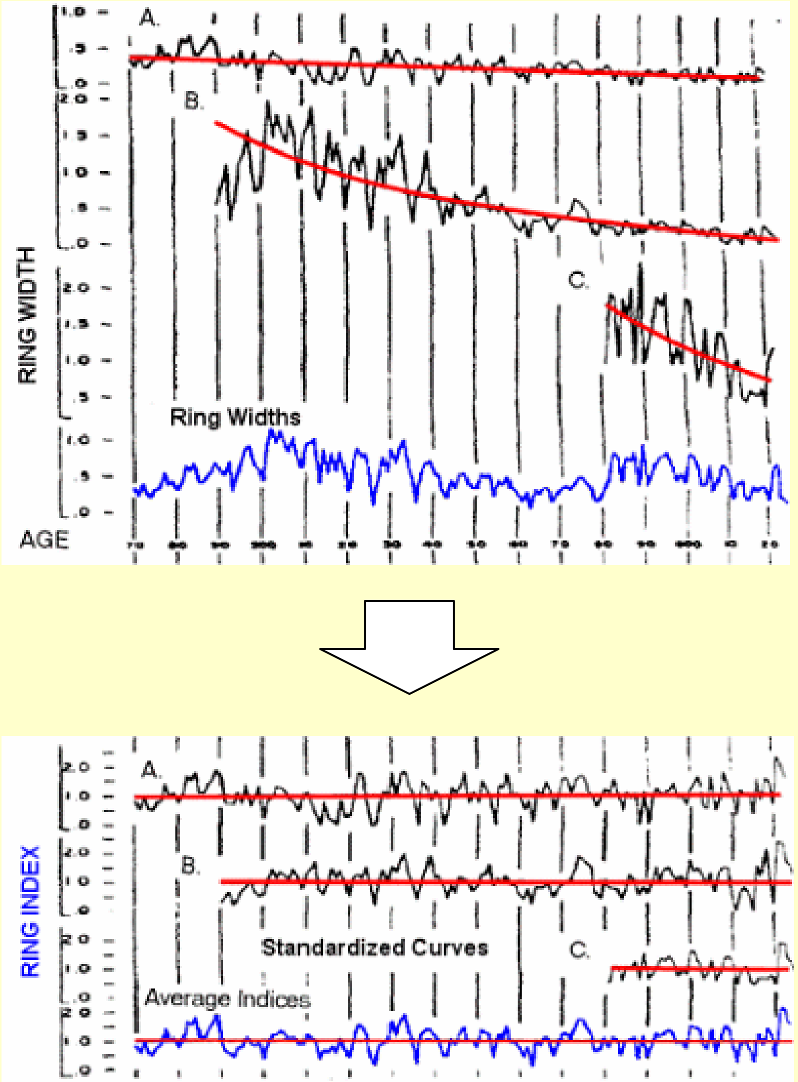
Compilation of Measured Tree-Ring Series



Steps in Building a Tree-Ring Chronology



Detrending the measured series

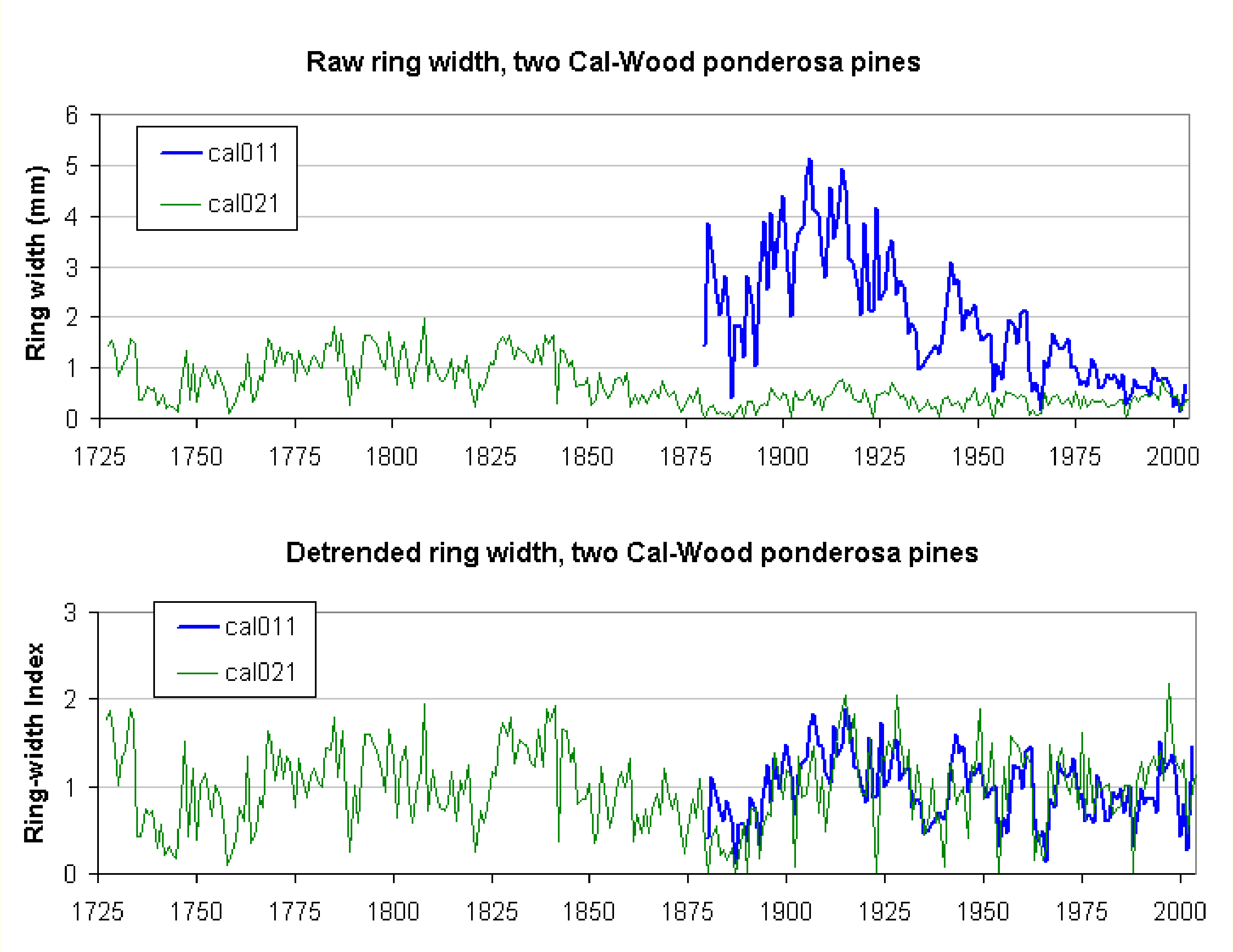


- Ring-width series typically have a declining trend with time
- Function of tree geometry, not aging *per se*
- These are low-frequency noise (i.e. non-climatic)

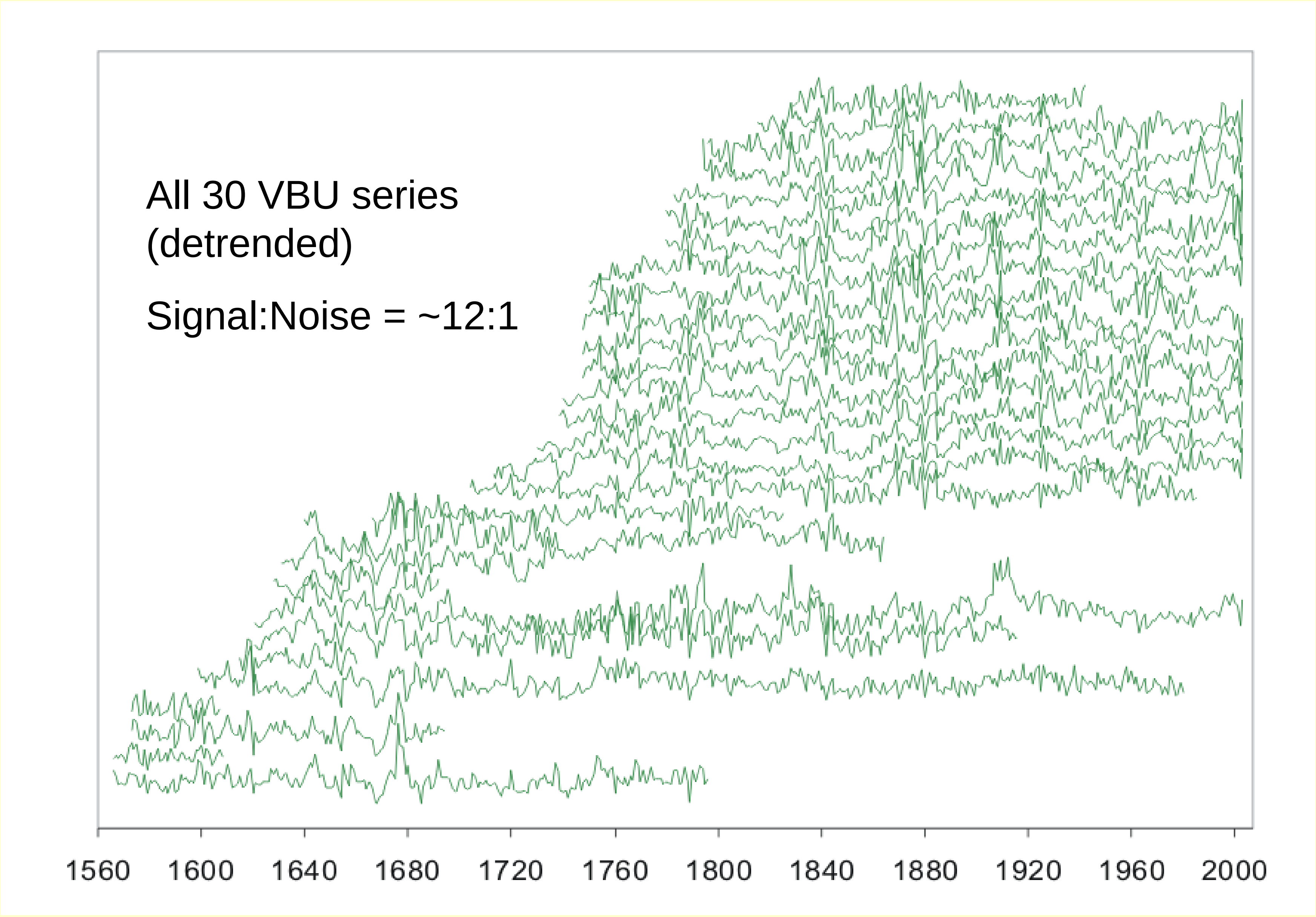
- Raw ring series are detrended with straight line, exponential curve, or spline

- these standardized curves are compiled into the site chronology

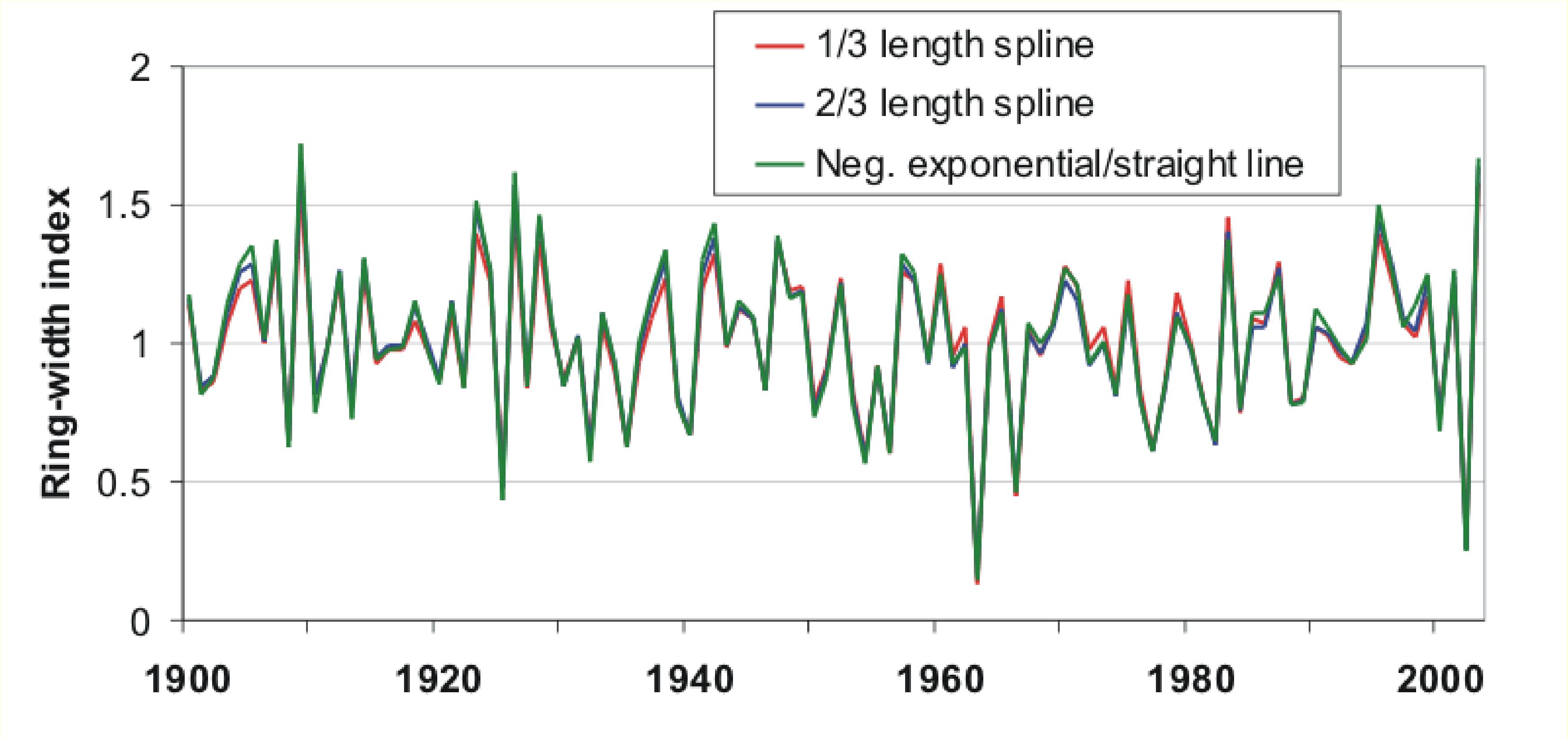
Detrending the measured series



Coherence of signal among series



Effects of detrending choice - VBU chronology



Sources of uncertainty

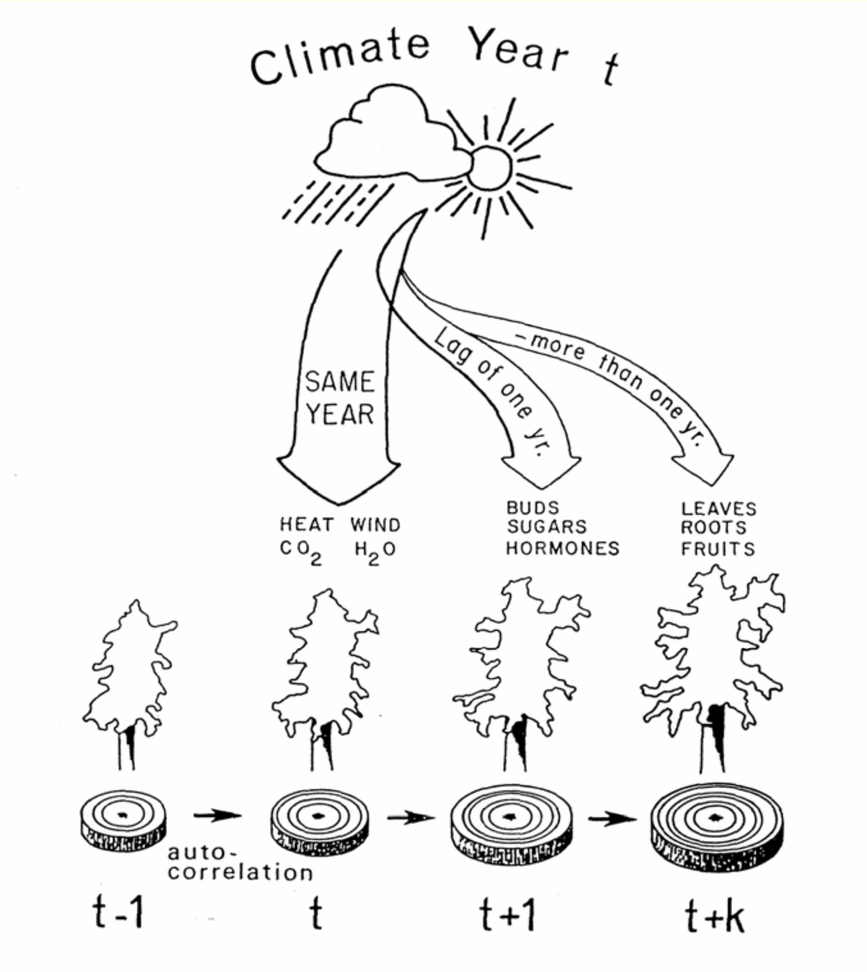
- choice of function(s) for detrending can affect final chronology (*figure above*)
- detrending removes the variation of periods equal to or longer than the series, including possible low frequency climate information

Persistence in tree growth from year to year

•The climate in a given year (t) influences growth in that year, but can also influence growth in succeeding years (t+1, t+k) through storage of sugars and growth of needles.

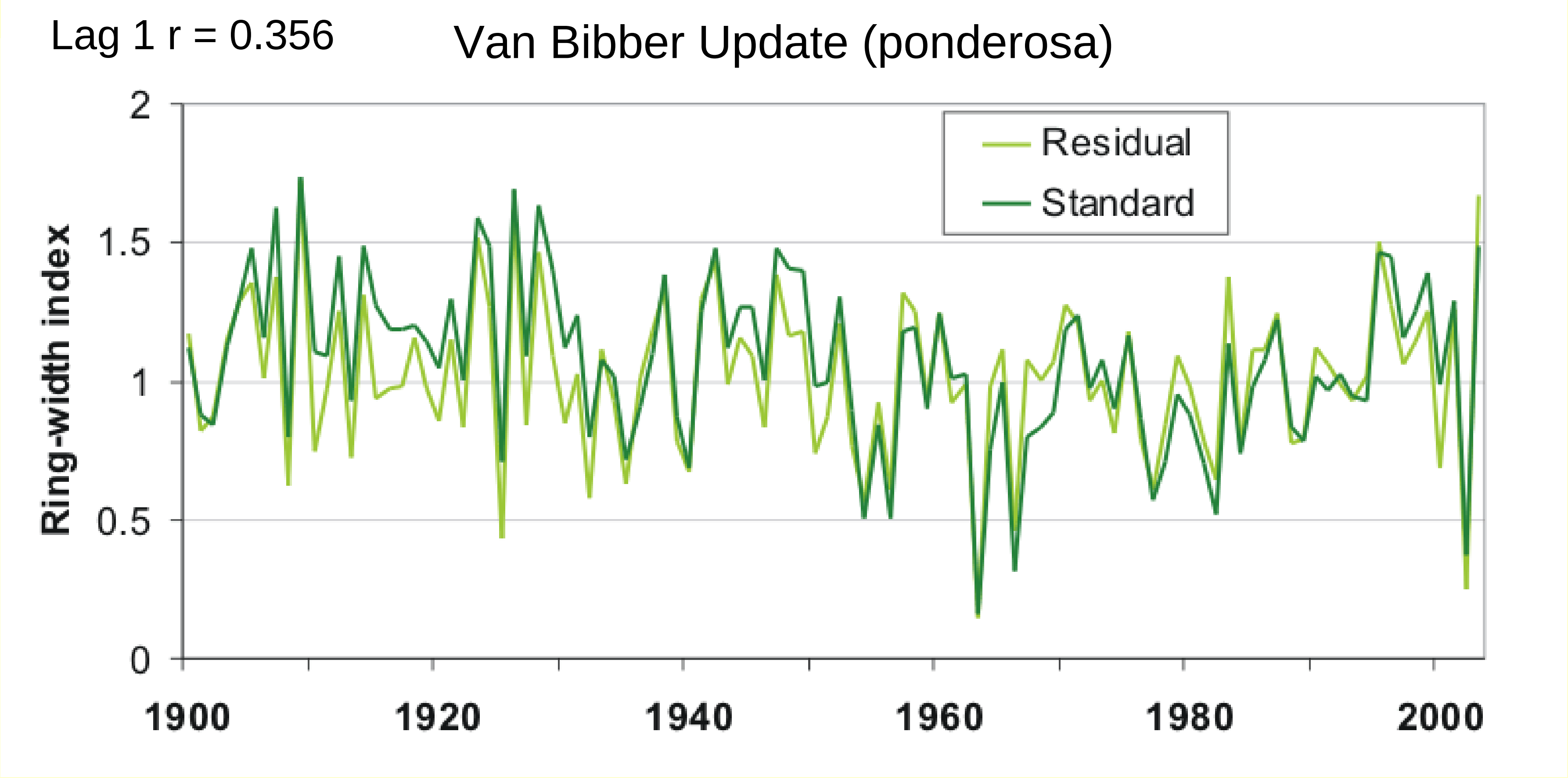
• Climate in year t is also statistically correlated with growth in previous years (t-1, t-k) because of this persistence.

• This persistence is considered to be biological, but can match the degree of persistence in annual flow series.



Persistence in the chronology can be retained or removed (prewhitening)

- *Standard chronology:* persistence in the series is retained
- *Residual chronology:* low order persistence is removed from each series before the chronology is compiled (also called a prewhitened chronology)



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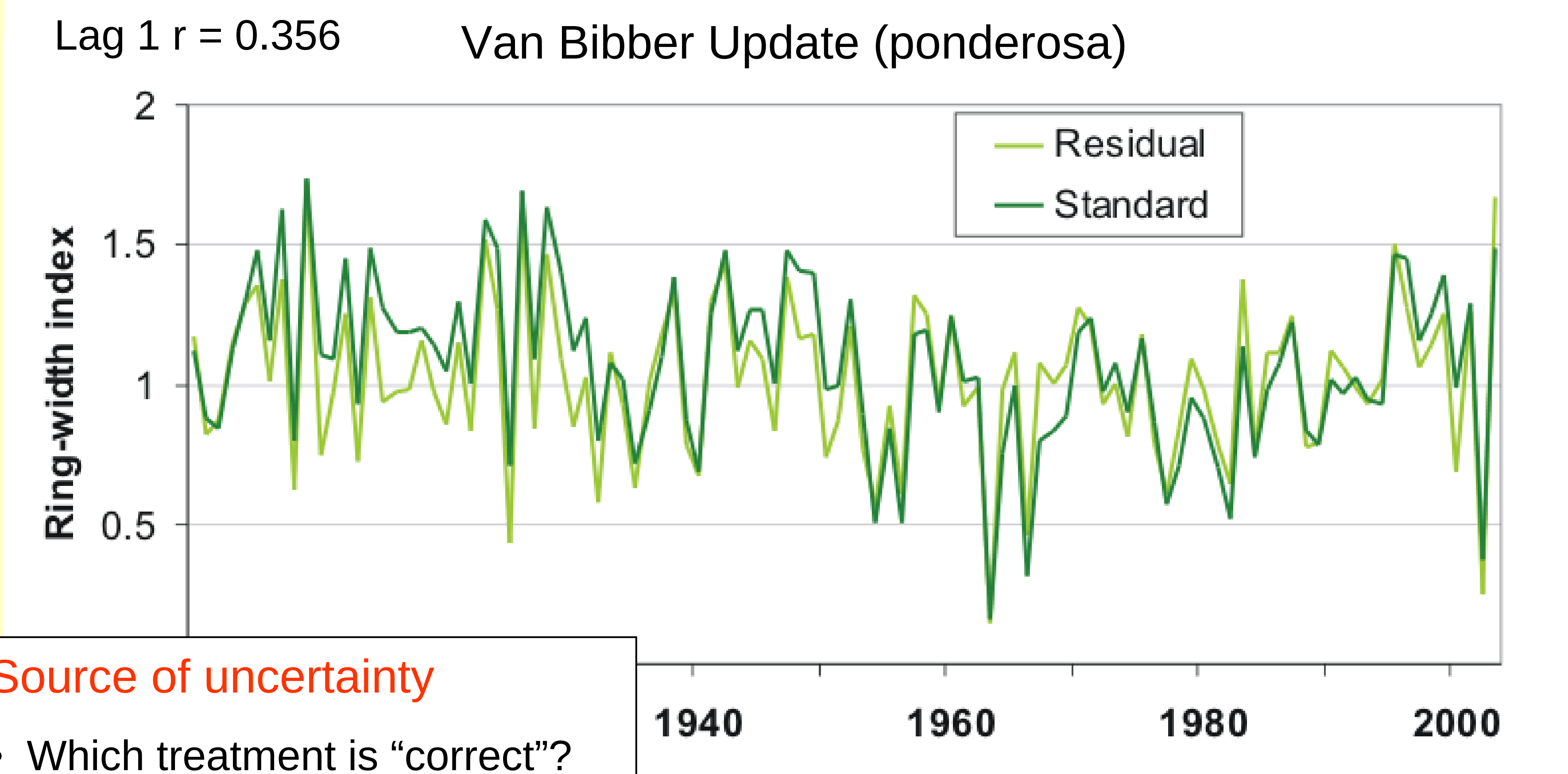


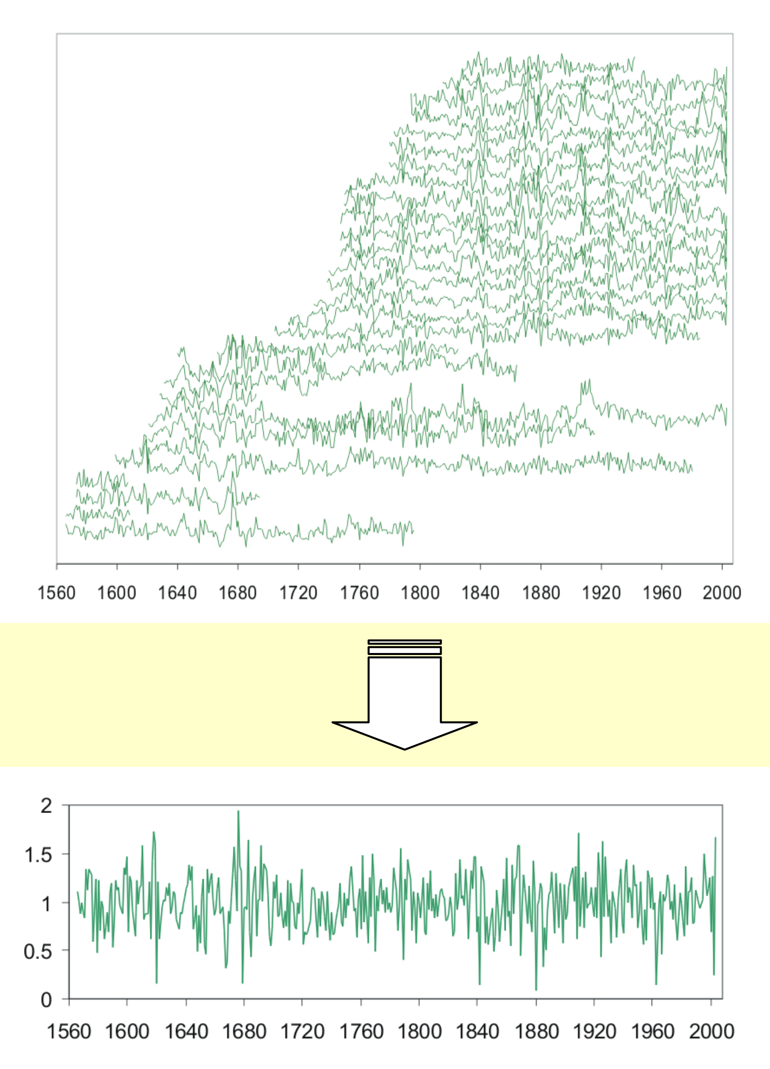
Source of uncertainty

- Which treatment is “correct”?

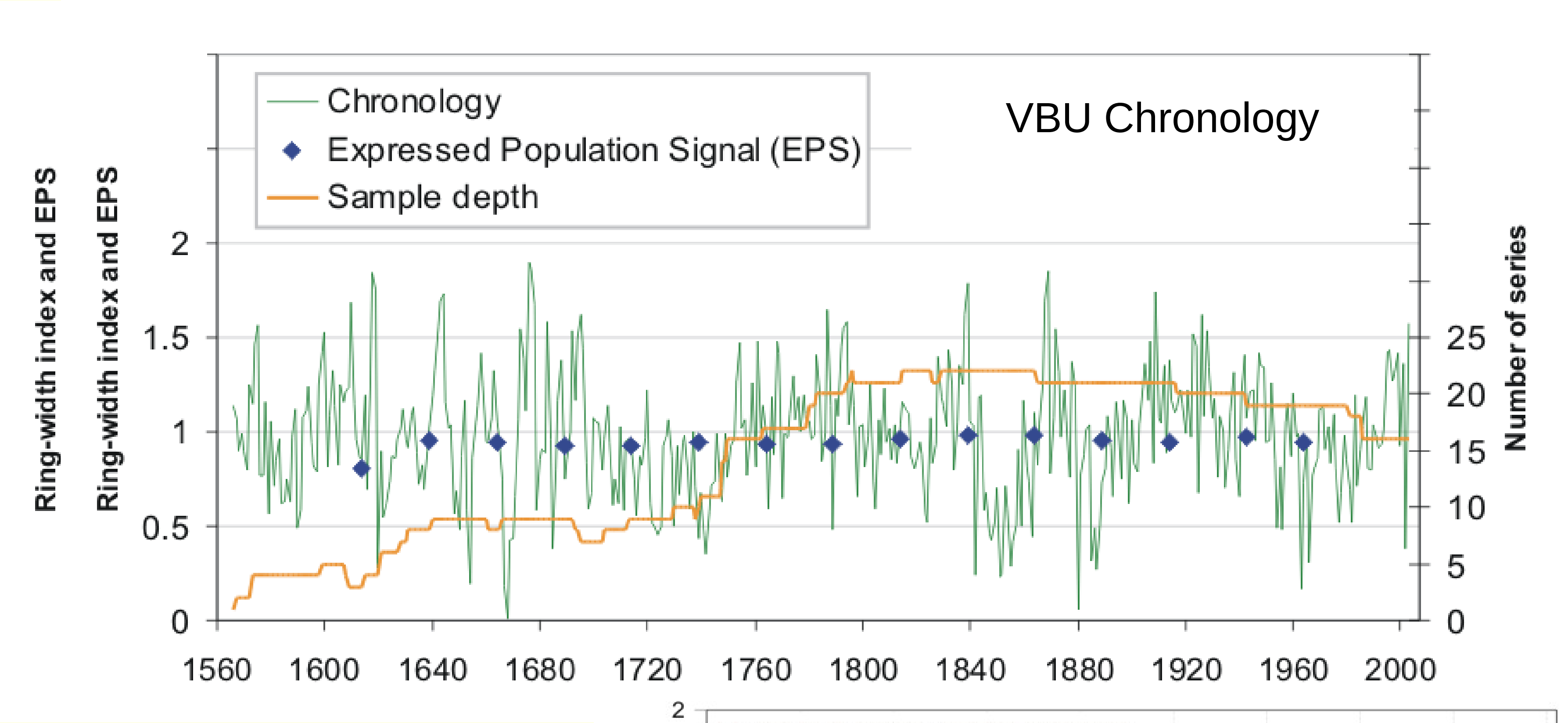
Compiling the chronology with ARSTAN

- The detrended and prewhitened (or not) series are averaged to create a site chronology, using a robust biweight mean, which reduces the effect of outliers

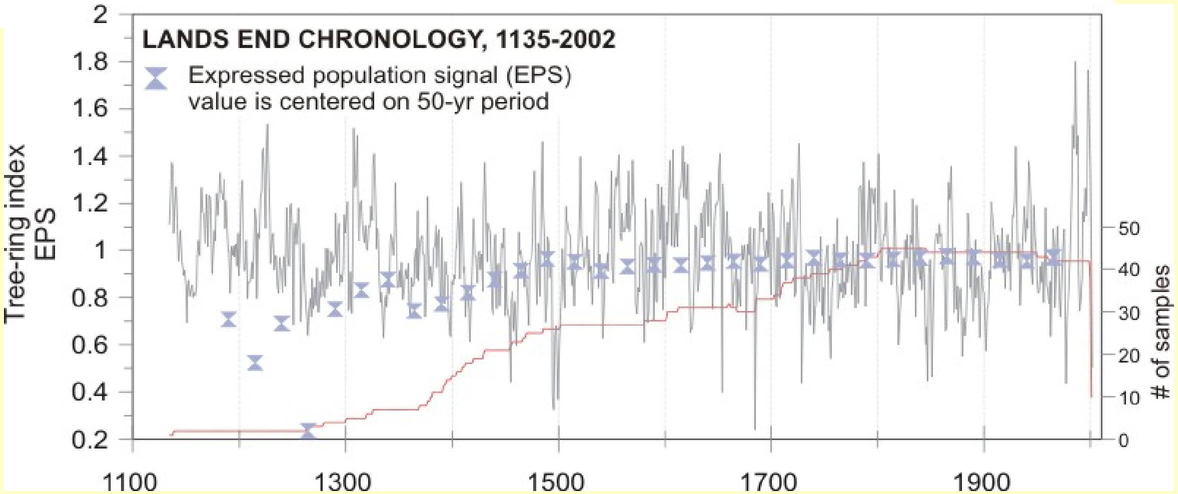
- In addition, since the sample size changes over time, the chronology variance is stabilized. This adjustment is typically based on the sample size information and average correlation between all series.



Chronology sample depth vs. signal strength

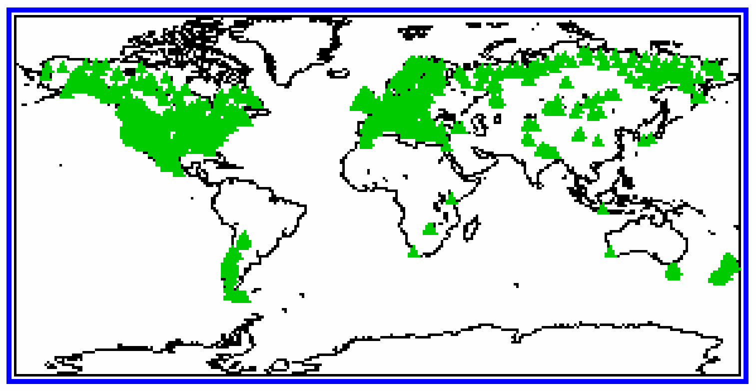


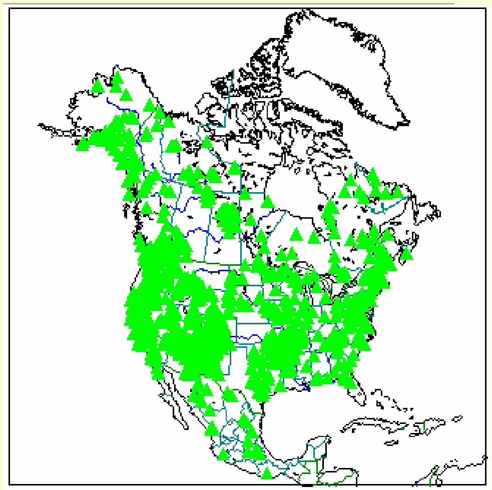
The Expressed Population Signal (EPS) is a measure of the percent common signal in the chronology. EPS should be close to 1.0. A threshold of 0.85 is commonly used.



Tree-ring data: Sources for chronologies

International Tree-Ring Data Bank (ITRDB)
http://www.ncdc.noaa.gov/paleo/treering.html





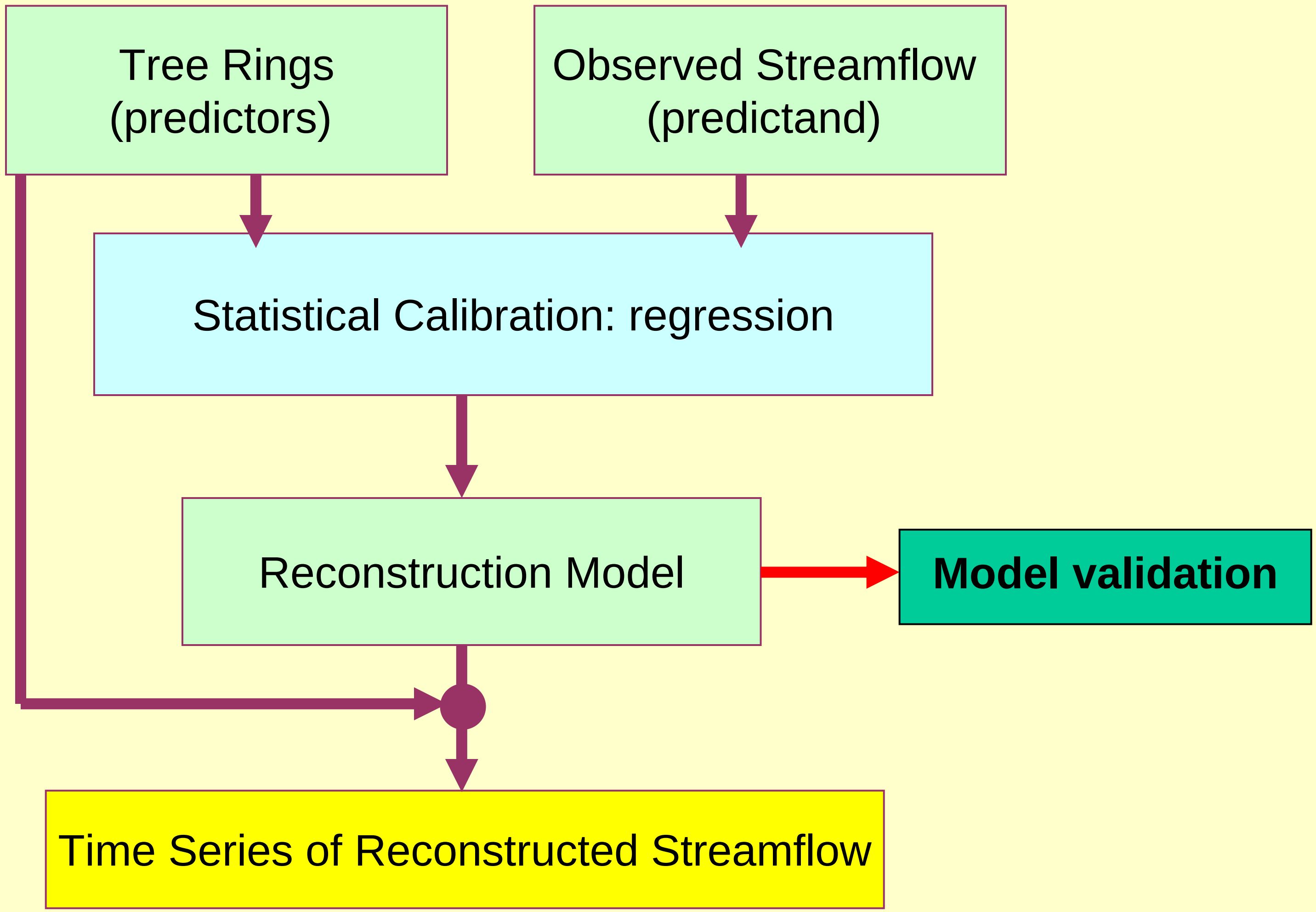
- ~2500 chronologies contributed from all over the world
- Can be searched by moisture-sensitive species, location, years

ITRDB Demo

Generating Streamflow Reconstructions from Tree-Ring Data

- Data selection and evaluation
- Reconstruction modeling strategies
- Model calibration and validation
- Assessing skill of the reconstruction

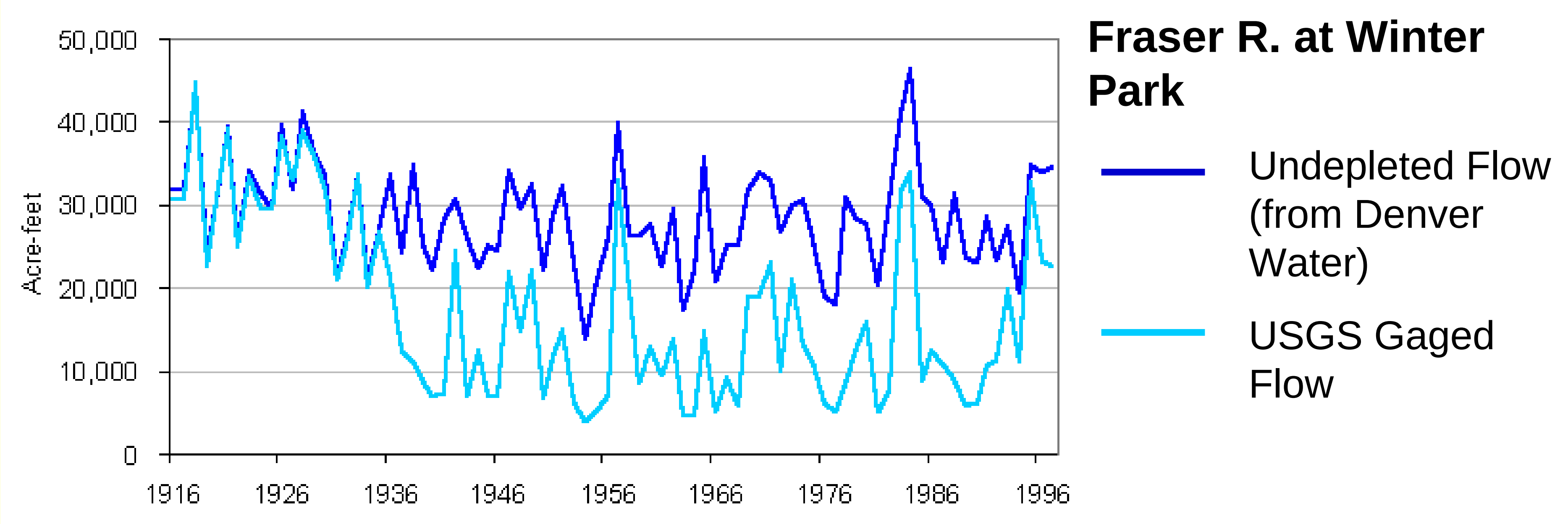
Overview of reconstruction methodology



based on Meko 2005

Gage Data

- **Length** – ideally >50 years for robust calibration with tree-ring data
- **Natural/undepleted record** – must be corrected for depletions, diversions, evaporation, etc.



About natural/undepleted flow records

- Record/estimates/models of depletions and diversions often inadequate, especially in early part of record
- The resulting uncertainties are added to typical errors in gage record (~5-10%)
- ***Our naïve view was:*** Flow record is “gold standard”, and where the tree-ring record varies from it, the trees are in error
- ***More realistic view:*** Flow record is a representation of actual flow, and discrepancies with tree-ring reconstruction *could* be due to errors in the flow record
- *The reconstruction can only be as good as the flow record on which it is calibrated*

Selecting chronologies

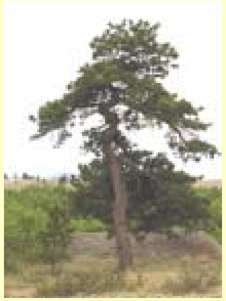
- **Moisture sensitive species** - in Colorado and Southwest: Douglas-fir, ponderosa pine, pinyon pine
- **Location** – from a region that is climatically linked to the gage of interest (more on this later)
- **Years -**

  Last year close to present for the longest calibration period possible

  First year as early as possible (>300 years) but in common with a number of chronologies

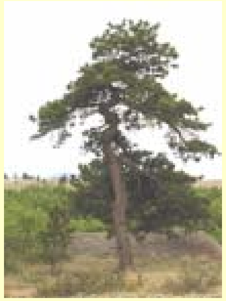
  - *reconstructions are limited by the shortest chronology*

ITRDB demo

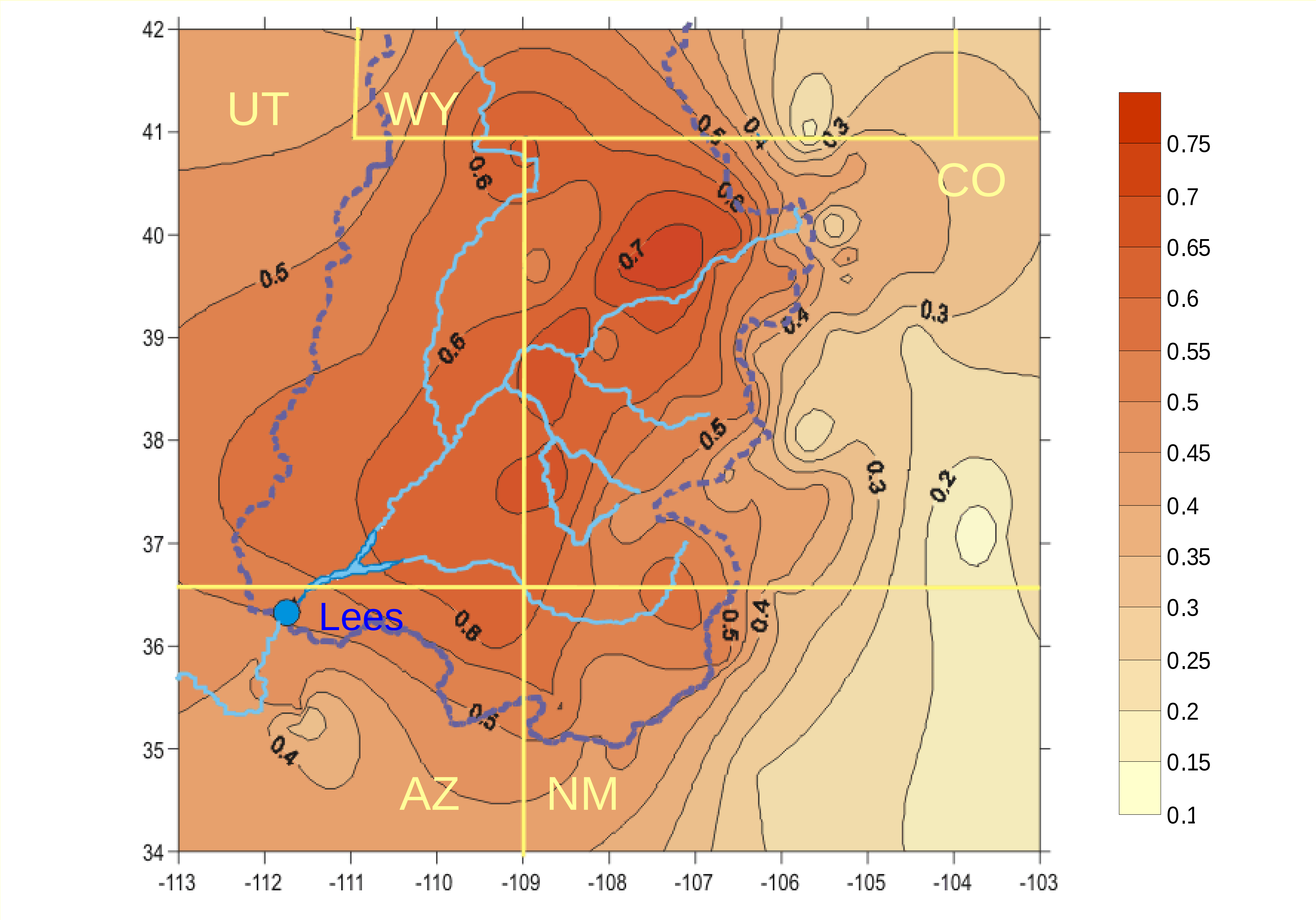


Physical linkage between tree growth and streamflow – regional climatology

- Chronologies up to ~600km from a gage may be significantly correlated because of a homogeneous climate across the region
- Because weather systems cross watershed divides, chronologies do not have to be in same basin as gage record
- At greater distances, any correlation could be due to *teleconnections*, which may not be stable over time



Correlations: UCRB chronologies - Lees Ferry streamflow

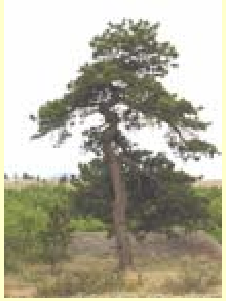


Testing time-stability of correlations

- If the relationship between a chronology and a flow record is stable over the past ~100 years, we assume the relationship was stable in previous centuries

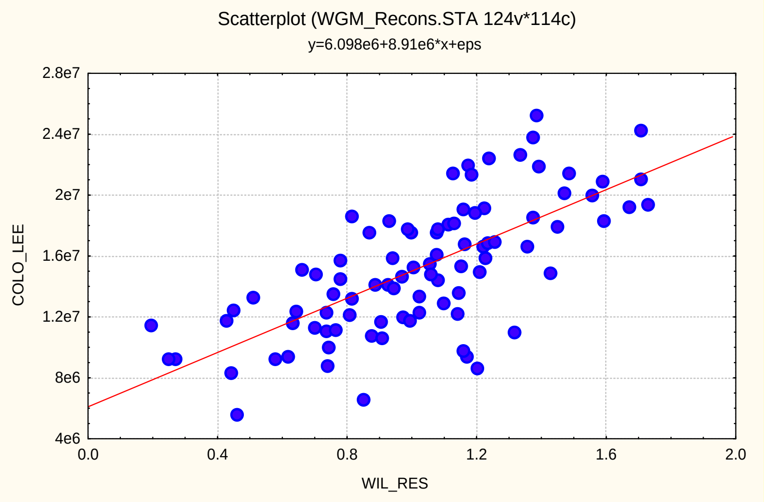
One way to test for the stability of a relationship over time:

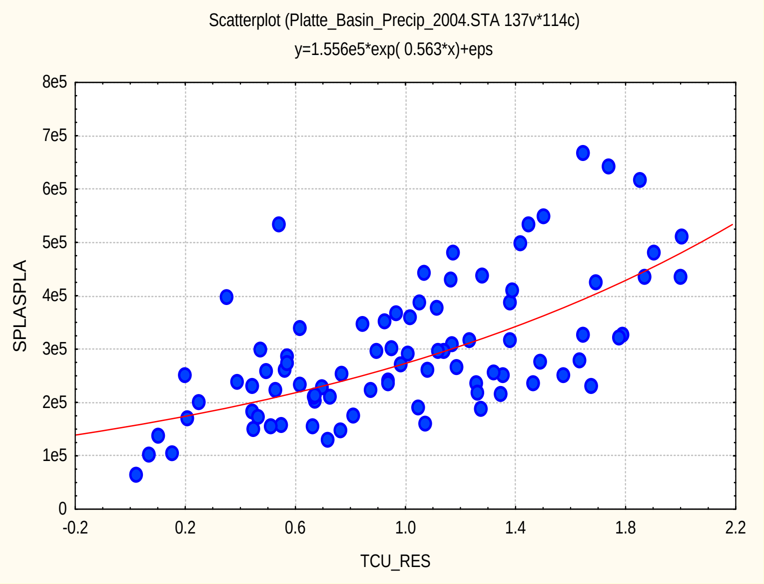
- Split-sample correlations test relationship in both halves of the calibration period
- If either half is not significant at $p < 0.05$ ($r = 0.30$ for 50-year period), then the relationship is considered unstable and the chronology is excluded from pool of possible predictors



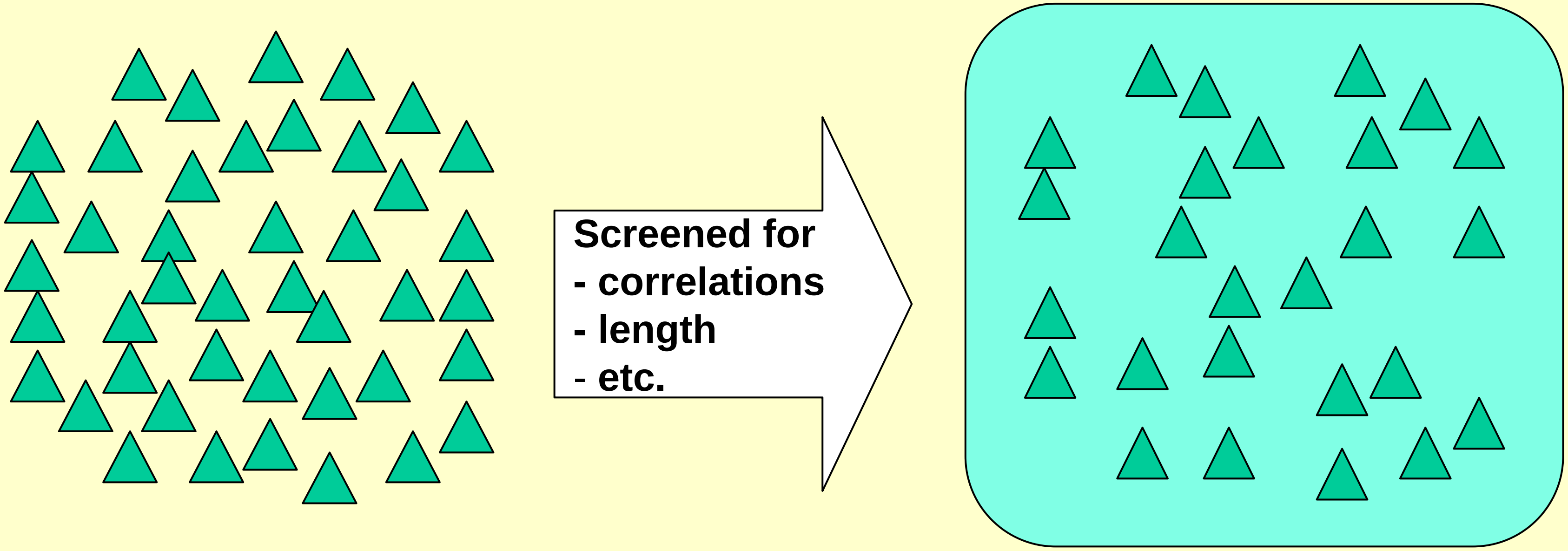
Assessing the shape of the tree ring-flow relationship

- The multiple linear regression model assumes the relationship between predictors (tree-ring data) and predictand (gage data) is linear
- If it is not, a transformation of the gage record is required (a log- transform is commonly used)





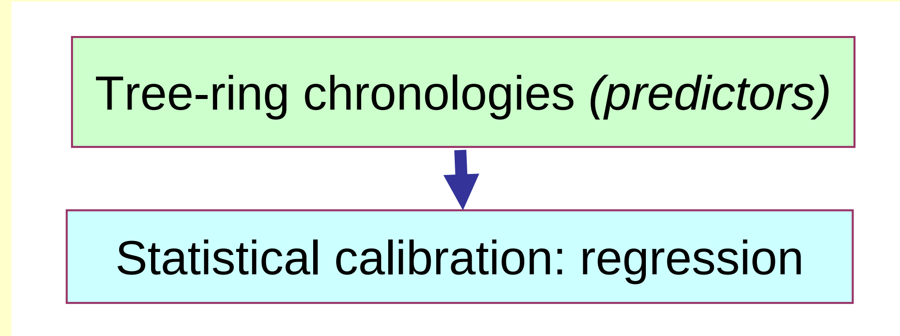
After *data selection and evaluation*, a pool of potential predictors is generated



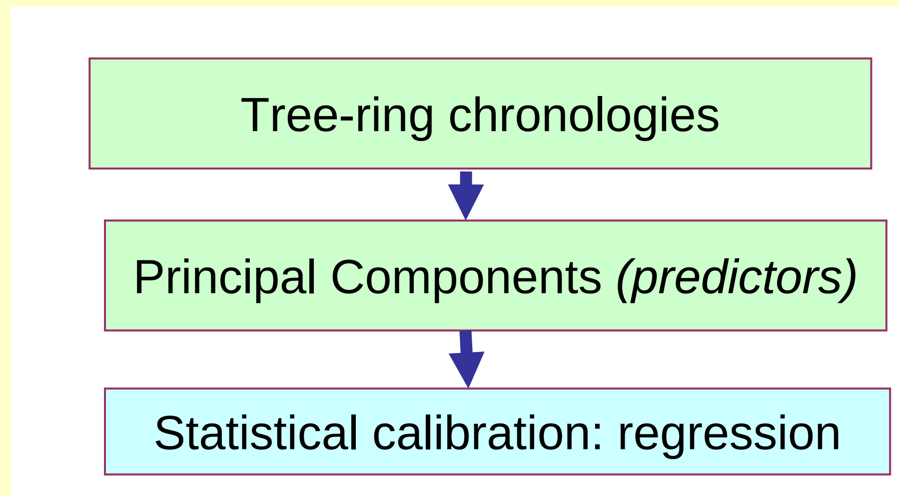
- Screening all available chronologies reduces the potential pool of predictor chronologies to be used in the modeling process
- It is important that the pool not be made unnecessarily large. As *n* predictors (chronologies) approaches *n* years in the calibration period, the likelihood of a meaningless predictor entering by chance alone increases

Reconstruction modeling strategies

- **Individual chronologies** are used as predictors in a stepwise or best subsets regression

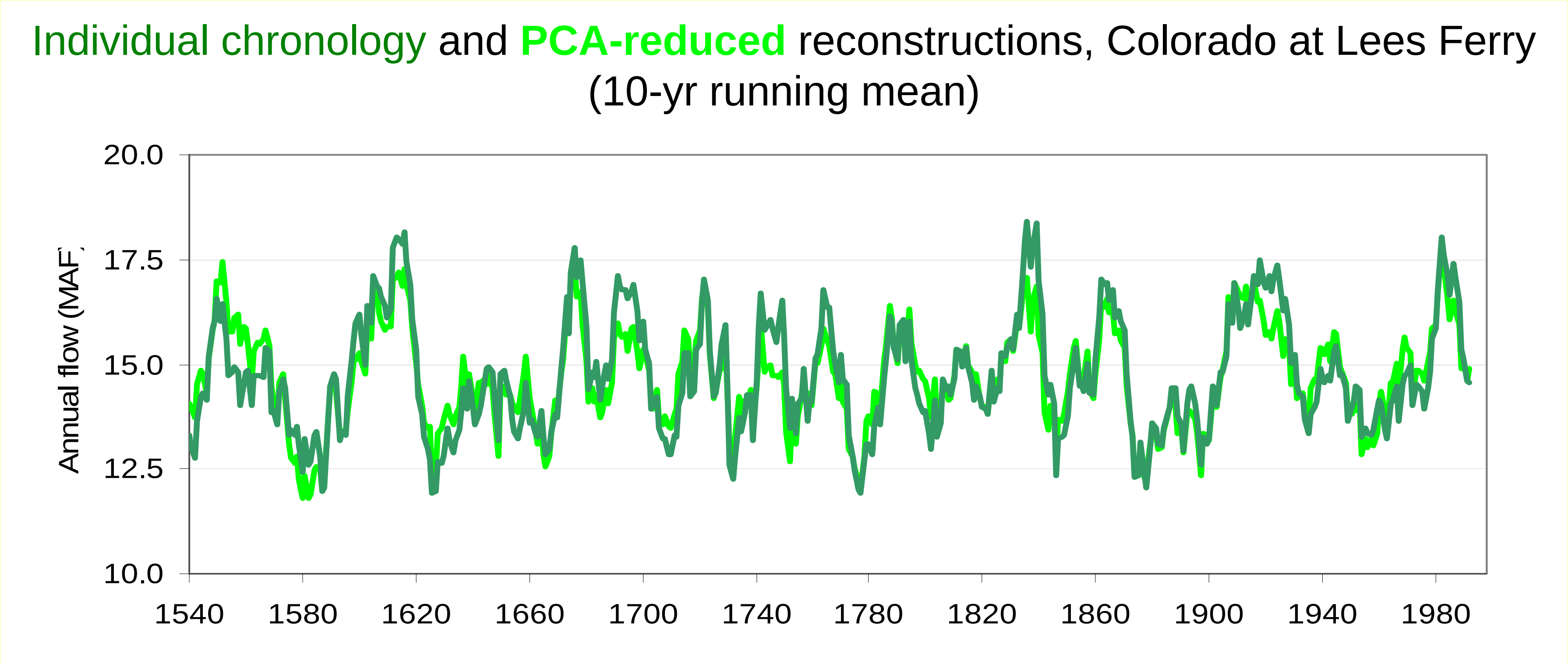


- **The set of chronologies is reduced** through Principal Components Analysis (PCA) and the components (representing modes of variability) are used as predictors in a regression



These are the most common, but many other approaches are possible (e.g., quantile regression, neural networks, non-parametric methods)

Reconstruction modeling strategies

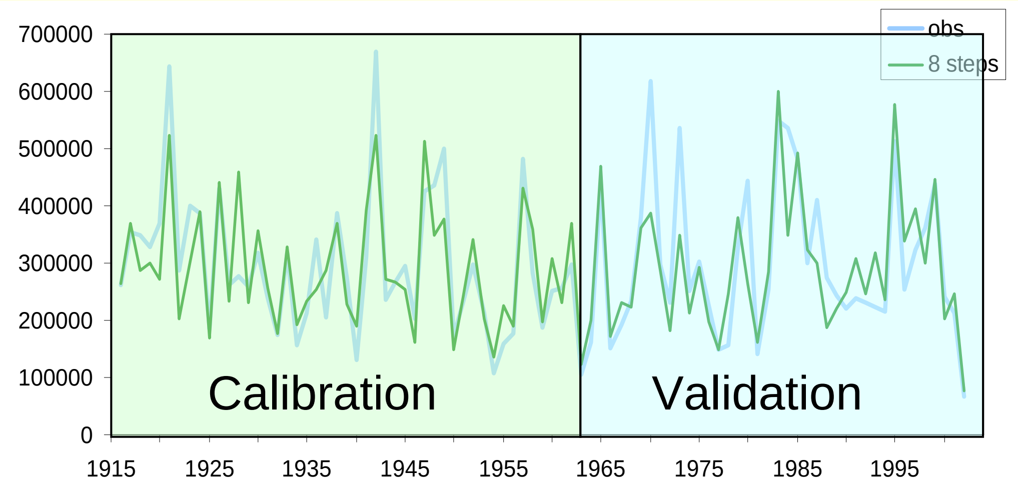


- The differences in final output between the two main strategies may not be very large, particularly if the primary predictor chronologies in the stepwise regression equation are dominant in the first few principal components

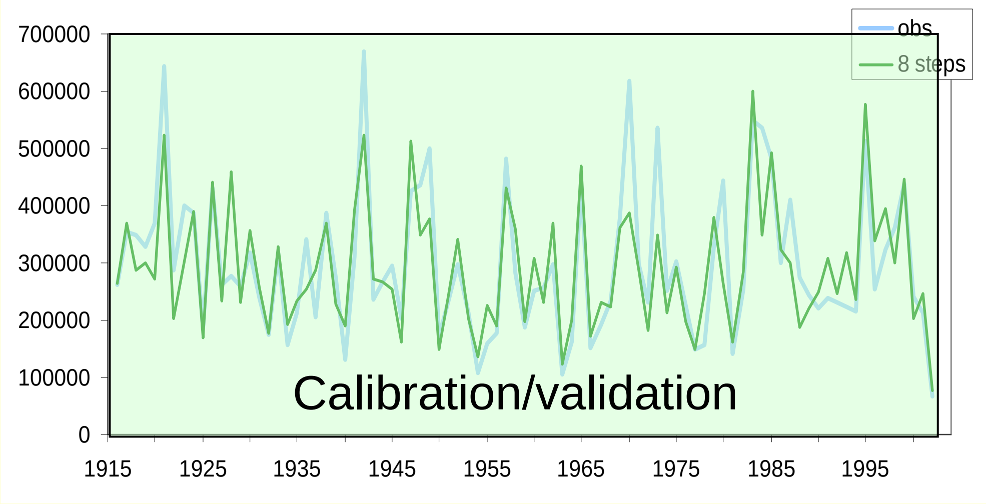
Model validation strategy

Goal: to calibrate model on a set of data, and validate the model on an independent set of data

Split-sample with independent calibration and validation periods



Cross-validation (“leave-one-out”) method

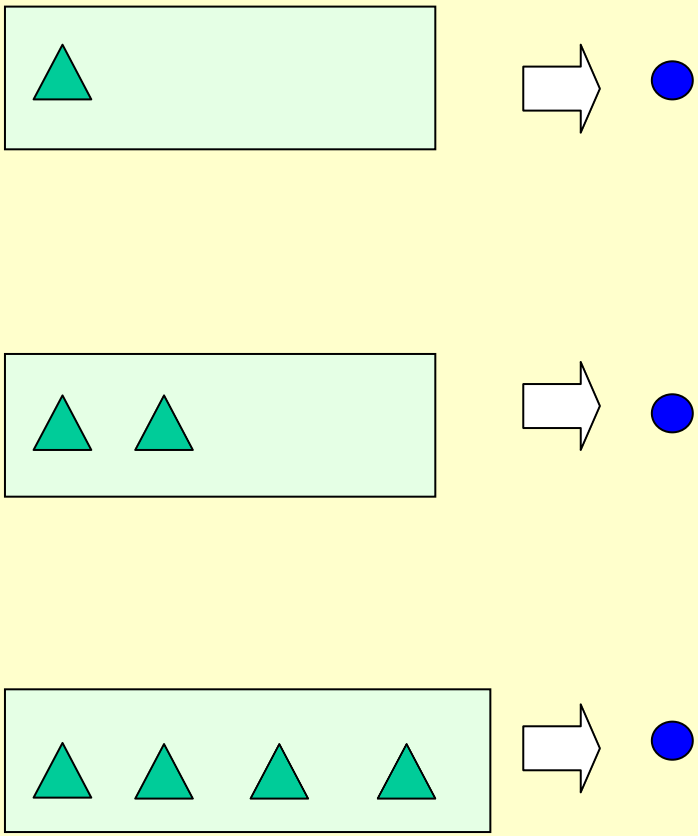


Model calibration: Forward stepwise regression

1) The chronology that explains the most variance in the flow record is selected as the first predictor in the regression

2) The chronology that explains the most *remaining unexplained* variance in the flow record is incorporated into the regression (repeat)

3) The process ends when no additional chronology significantly improves the fit of the regression to the flow record



Model Calibration: Forward Stepwise Regression

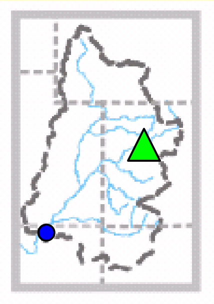
- The result is a weighted linear combination of tree-ring chronologies that together estimate a portion of the variance in the gage record

$$y = a_1x_1 + a_2x_2 + \ldots a_nx_n + b$$

LeesFerry = - 2462.05 + 3878.393 DJM + 4258.509 DOU + 1766.509 NPU + 5417.487 PUM – 5588.319 RED + 6416.88 TRG + 4612.965 WIL

- **The model is only tentative at this point and must be validated and assessed for skill**

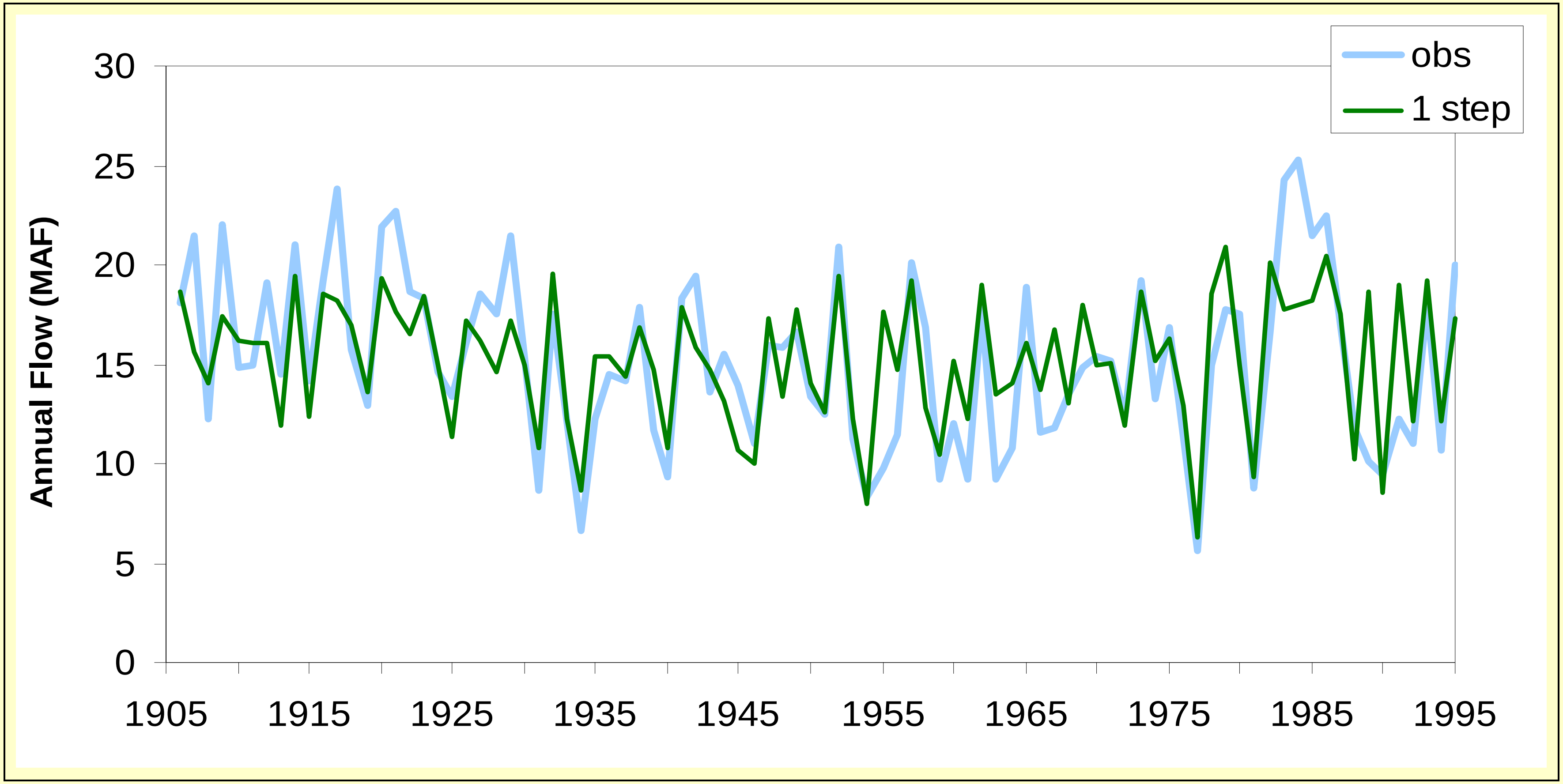
Colorado at Lees Ferry - forward stepwise regression



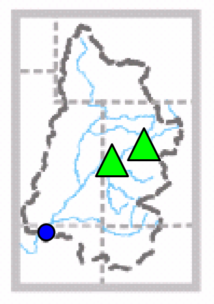
TRG

Variance Explained

55%



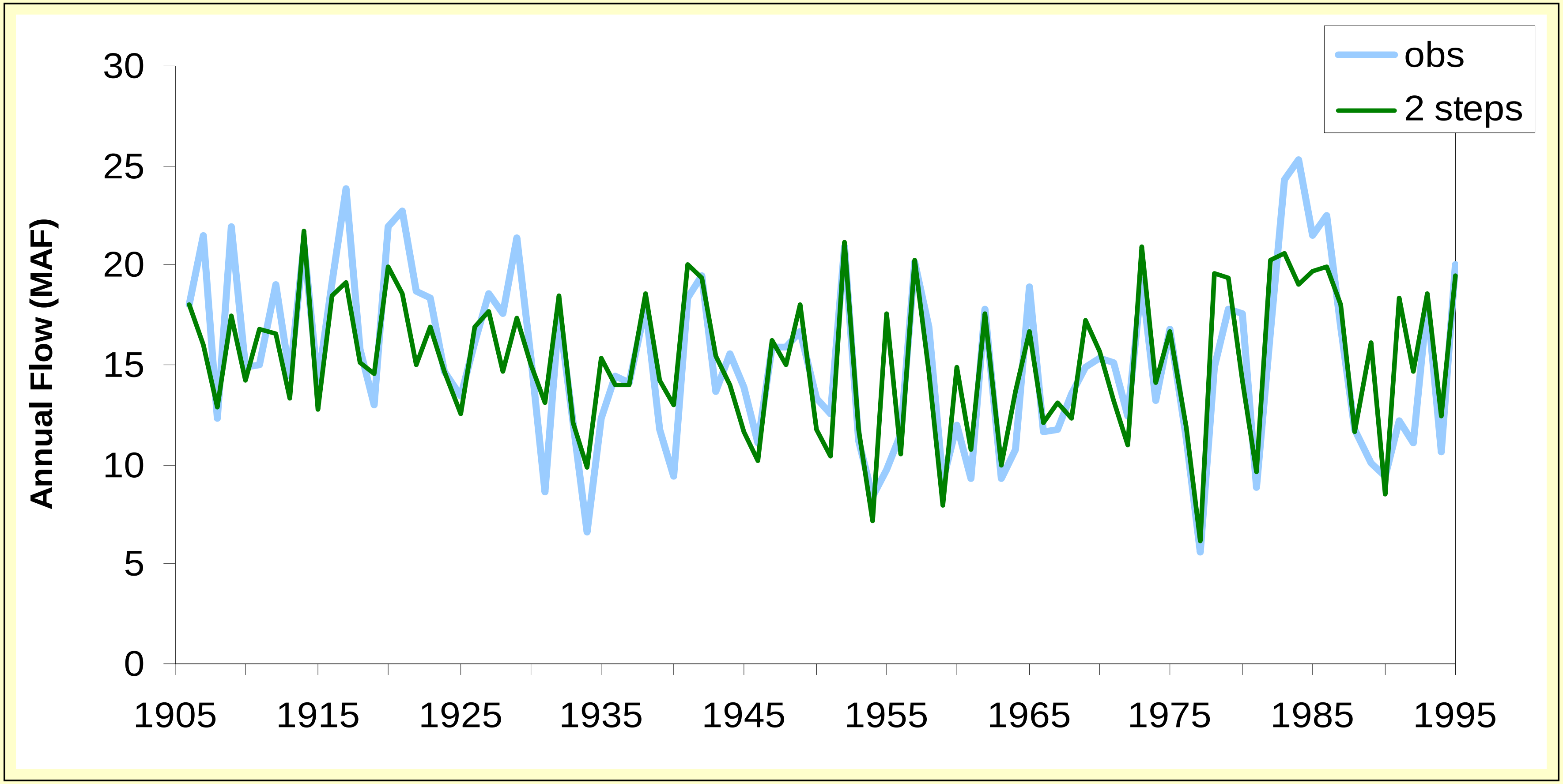
Colorado at Lees Ferry - forward stepwise regression



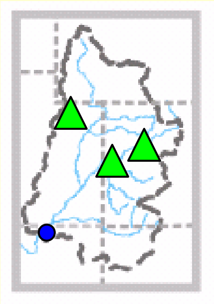
TRG + WIL

Variance Explained

67%



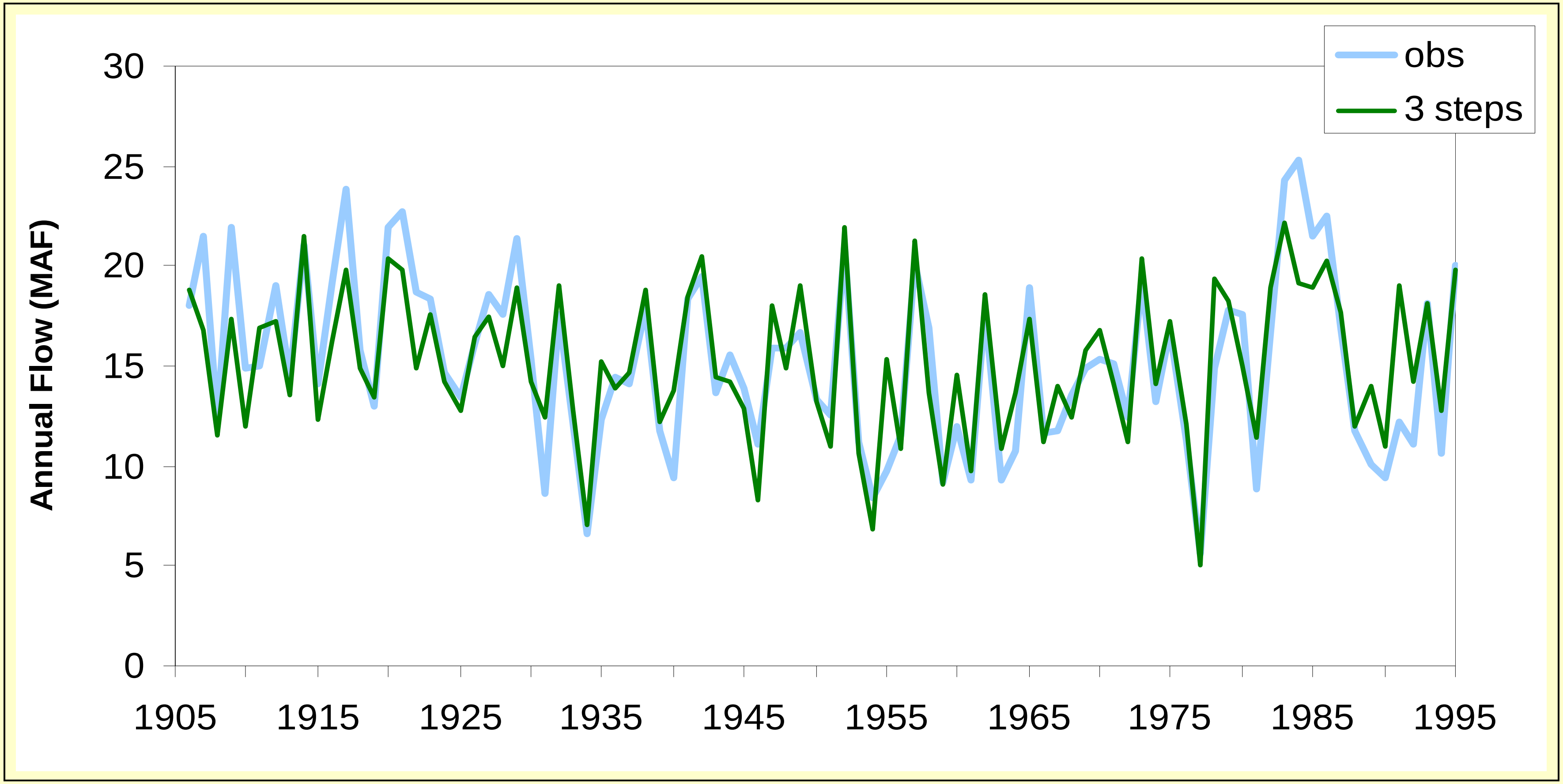
Colorado at Lees Ferry - forward stepwise regression



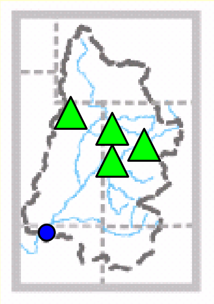
Variance Explained

72%

TRG + WIL + DJM



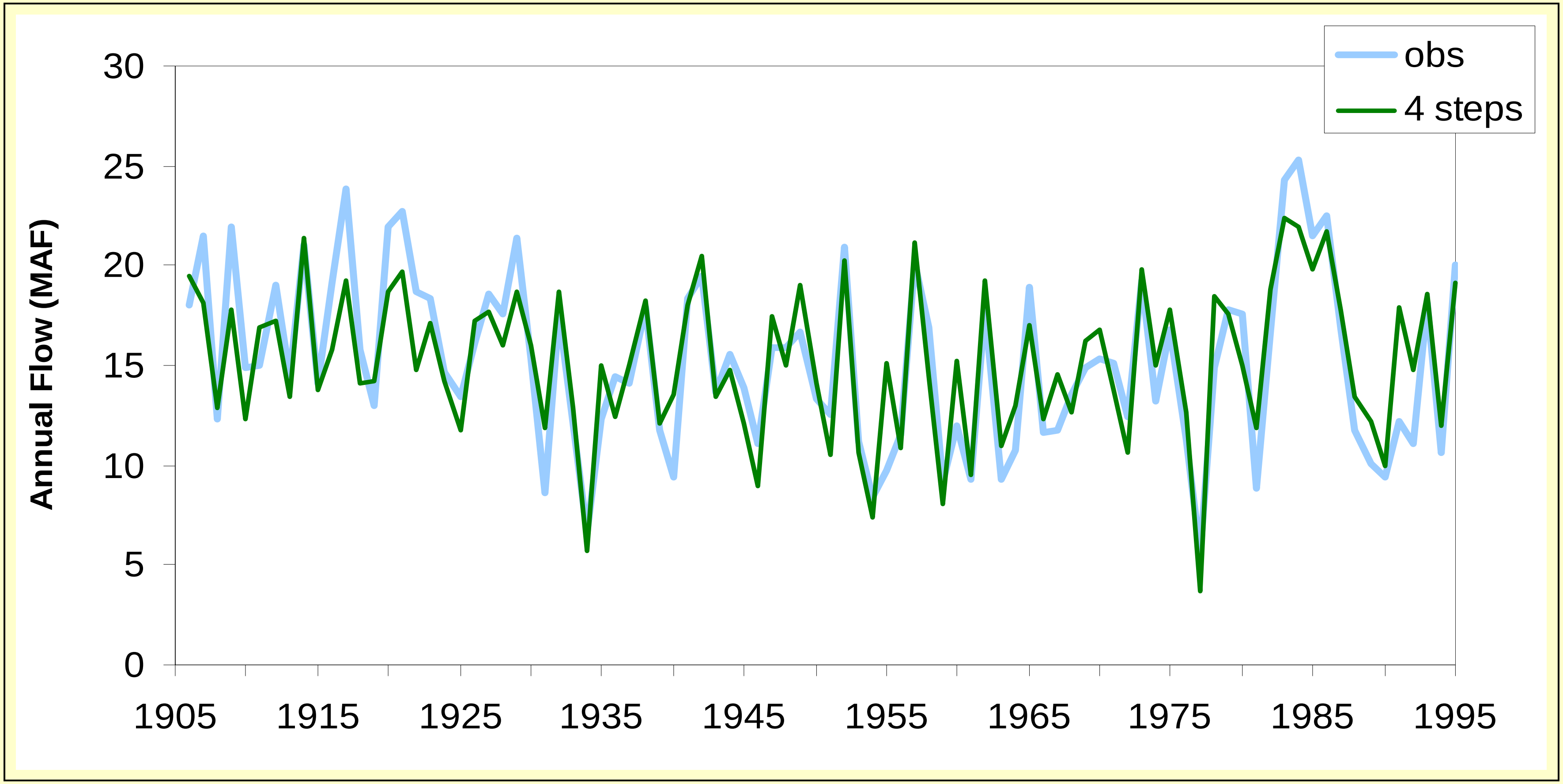
Colorado at Lees Ferry - forward stepwise regression



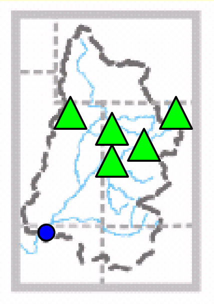
Variance Explained

75%

TRG + WIL + DJM + DOU



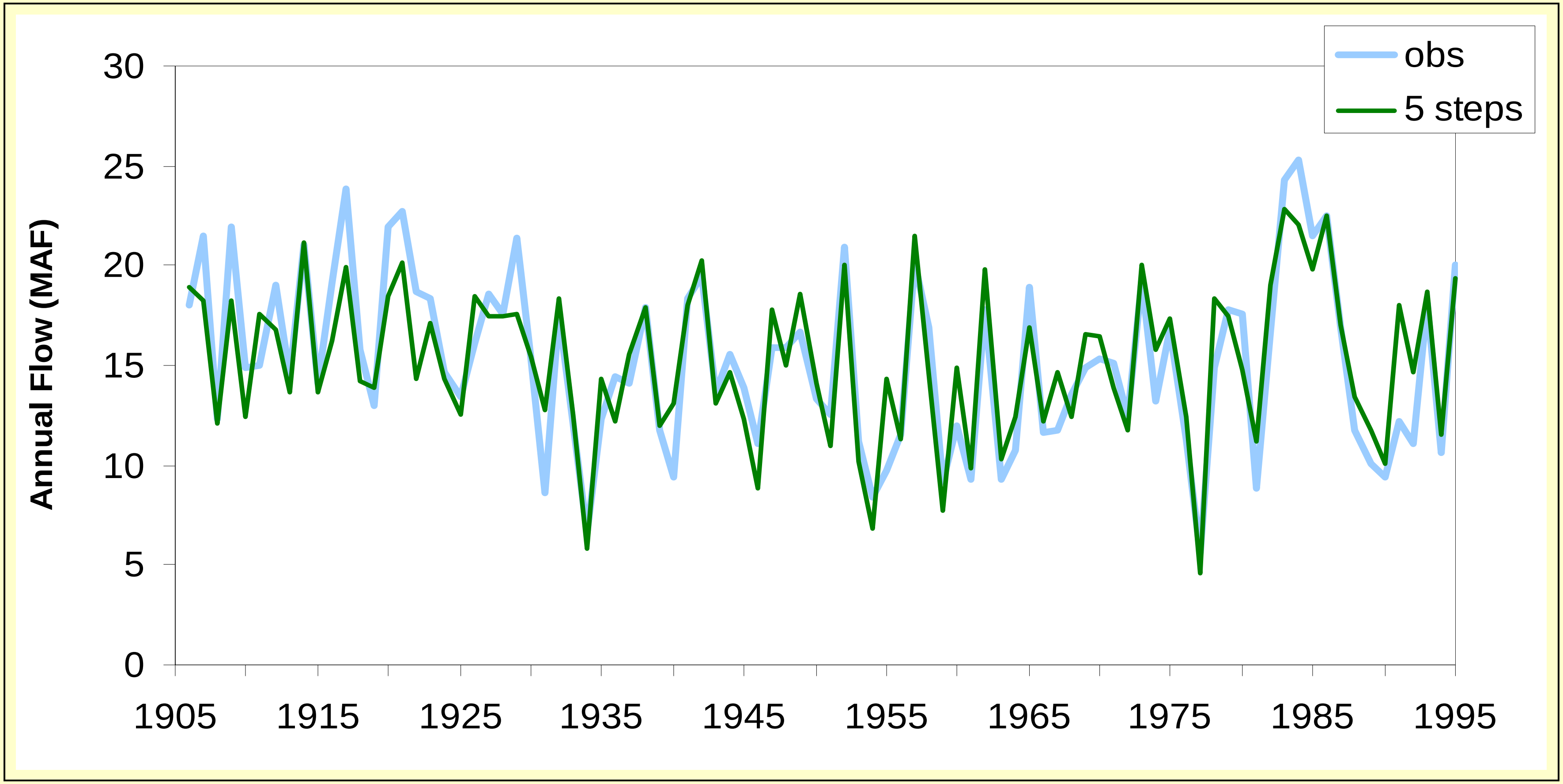
Colorado at Lees Ferry - forward stepwise regression



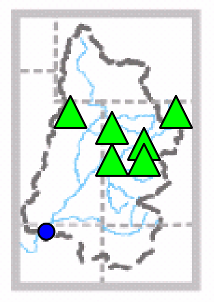
Variance Explained

77%

TRG + WIL + DJM + DOU + NPU



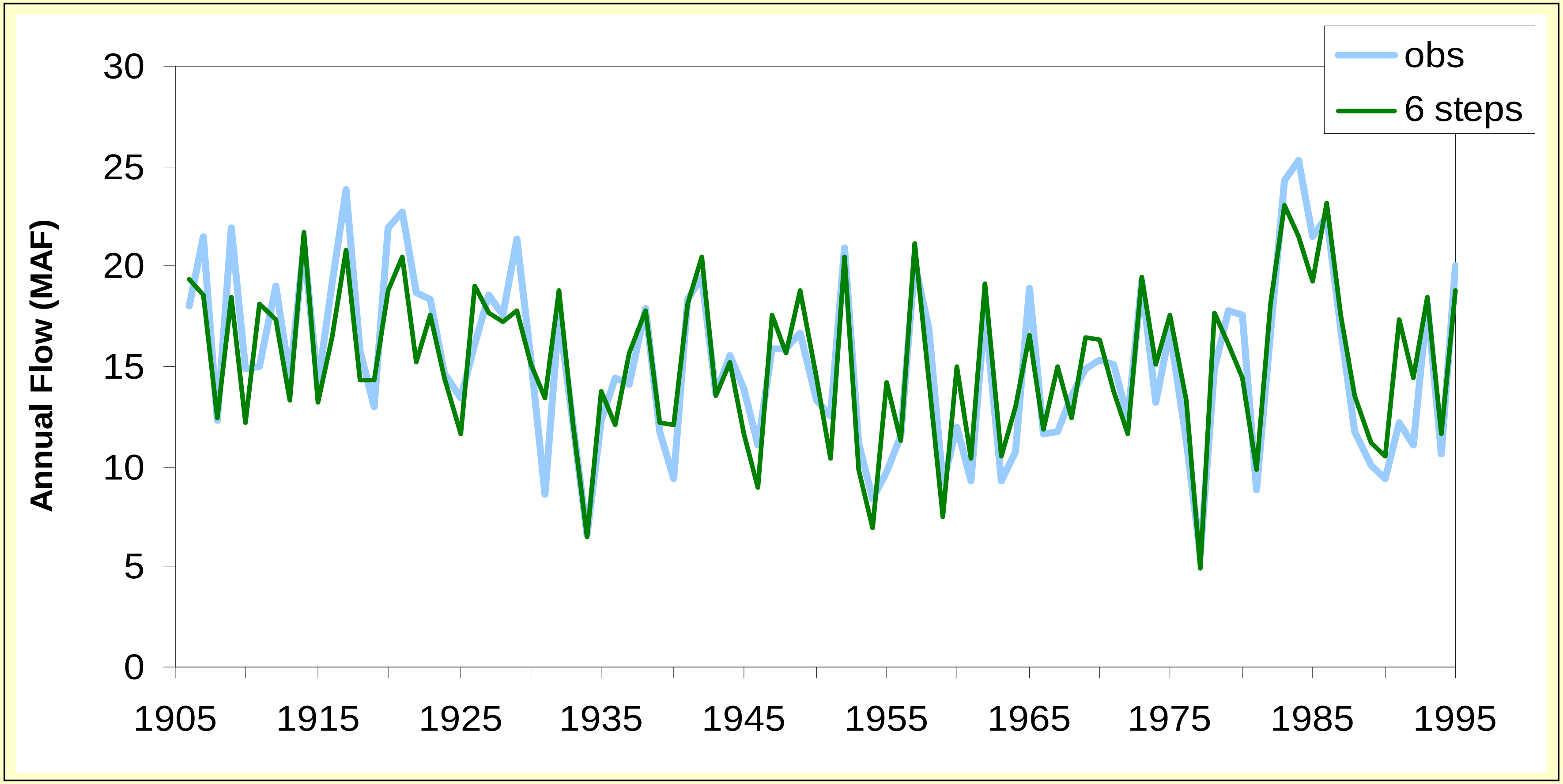
Colorado at Lees Ferry - forward stepwise regression



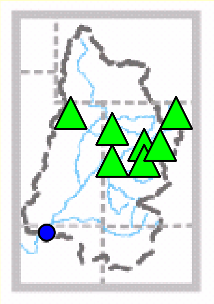
Variance Explained

TRG + WIL + DJM + DOU + NPU + RED

79%



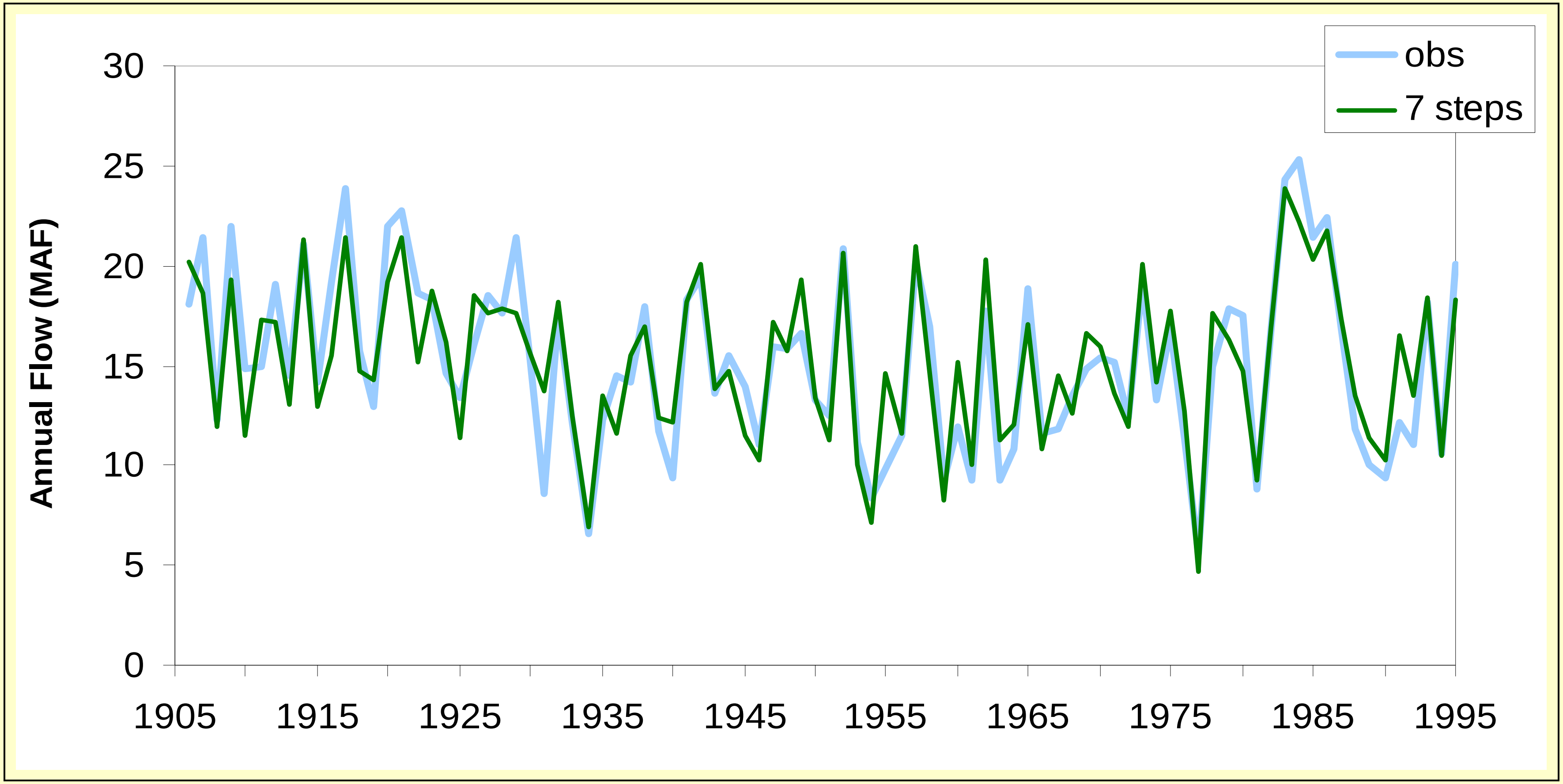
Colorado at Lees Ferry - forward stepwise regression



Variance Explained

TRG + WIL + DJM + DOU + NPU + RED + PUM

81%



Model validation and skill assessment

- Are regression assumptions satisfied?
- How does the model validate on data not used to calibrate the model?
- How does the reconstruction compare to the gage record?

Are regression assumptions satisfied?

Analysis of residuals

Residuals are assumed to have:

- NO significant trend with time
- NO significant changes in variance over time
- NO significant autocorrelation
- NO significant correlation with the model estimates
- NO significant correlation with individual predictors
- normal distribution

How does the model validate on data not used to calibrate the model?

Validation statistics – based on withheld data or generated in cross-validation process, compared to observed data

- *Root mean squared error of validation ($RMSE_v$)* - measure of the average error for the validation period; computationally equivalent to standard error of the estimate on the calibration data

- *Reduction of error (RE)* - measure of the skill of a model relative to a “no-knowledge” prediction (here, we use the mean of the gage record for the calibration data); computationally similar to R_2 from the calibration

Calibration and validation statistics for selected reconstruction models

Gage	R^2	RE	Std. Err.	RMSE
Boulder Creek at Orodell	0.65	0.6	11396	11713
Rio Grande at Del Norte	0.76	0.72	113100	117834
Colorado R at Lees Ferry	0.81	0.76	1983500	2090633
Gila R. near Solomon	0.59	0.56		
Sacramento R.	0.81	0.73	0.083*	0.098*

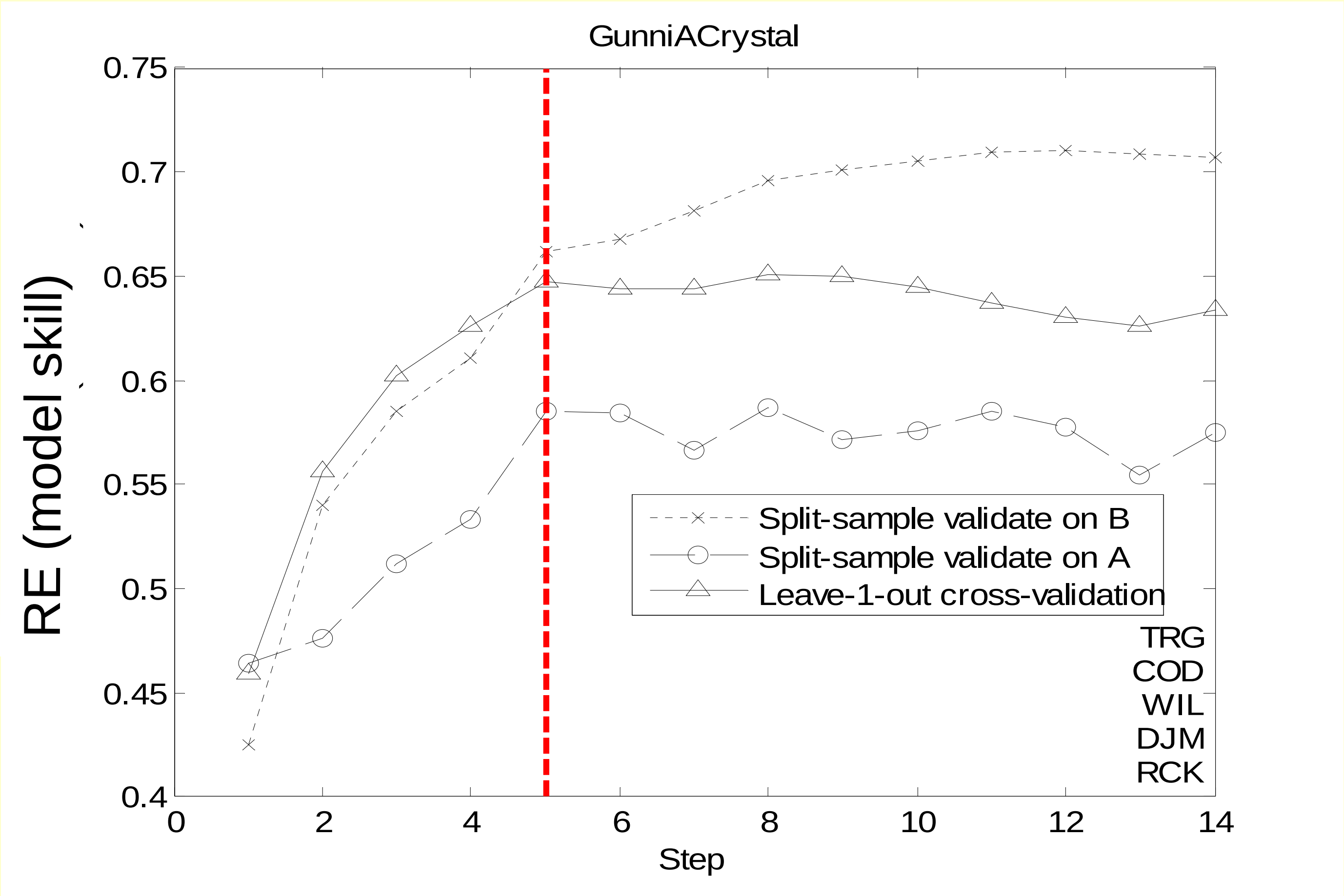
- These statistics will generally be higher for larger basins
- What is a “good” value for R^2? No hard and fast rules, but we hope for more than 0.50, but a very high value could signify model overfit.

* because of log-transform of flow data, these values are in log-units

Prevention of overfitting

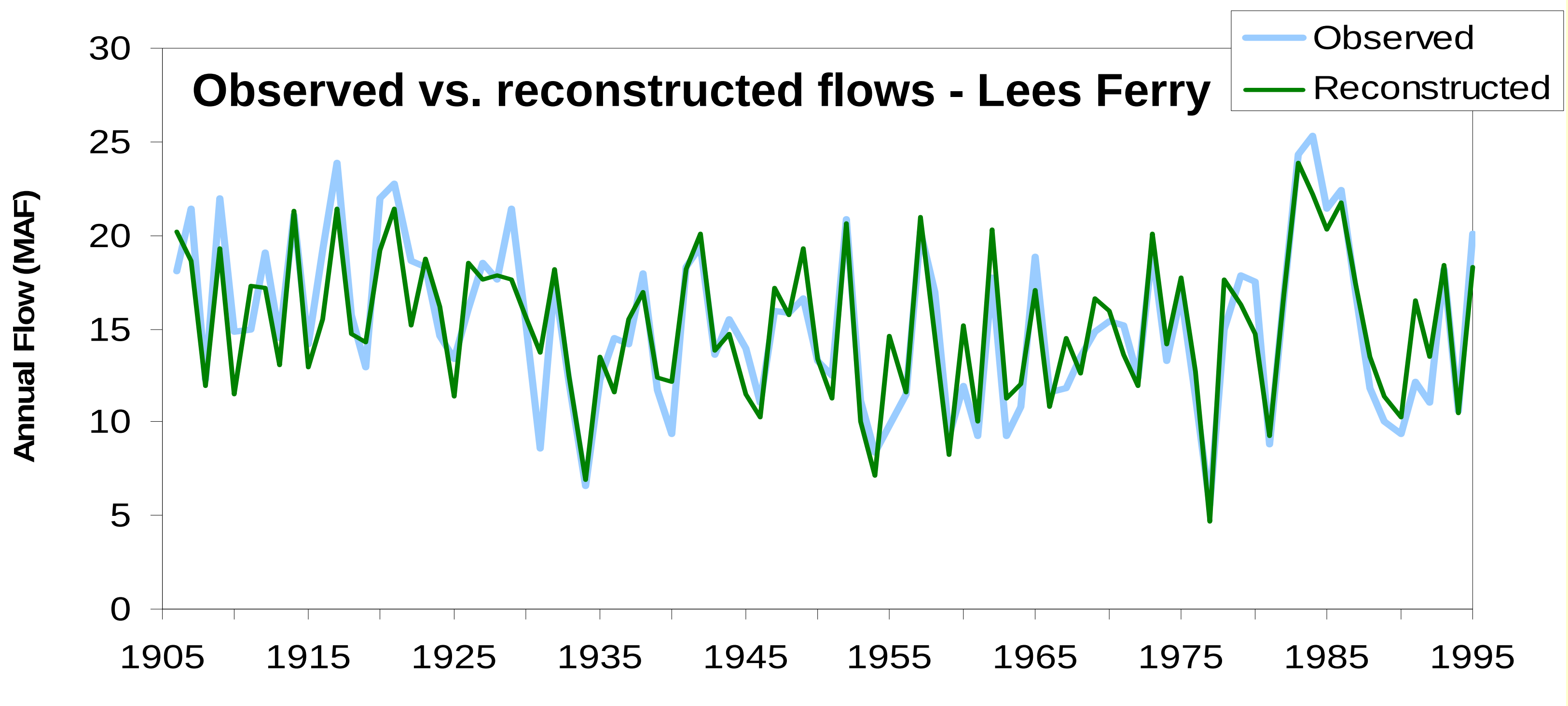
An over-fit model is very highly tuned to the calibration period, but doesn't do as well with data not in the calibration period

Prevention of overfitting



- For this particular model (Gunnison at Crystal Res.), the validation RE is not improved appreciably with more than 5 predictors (red line)

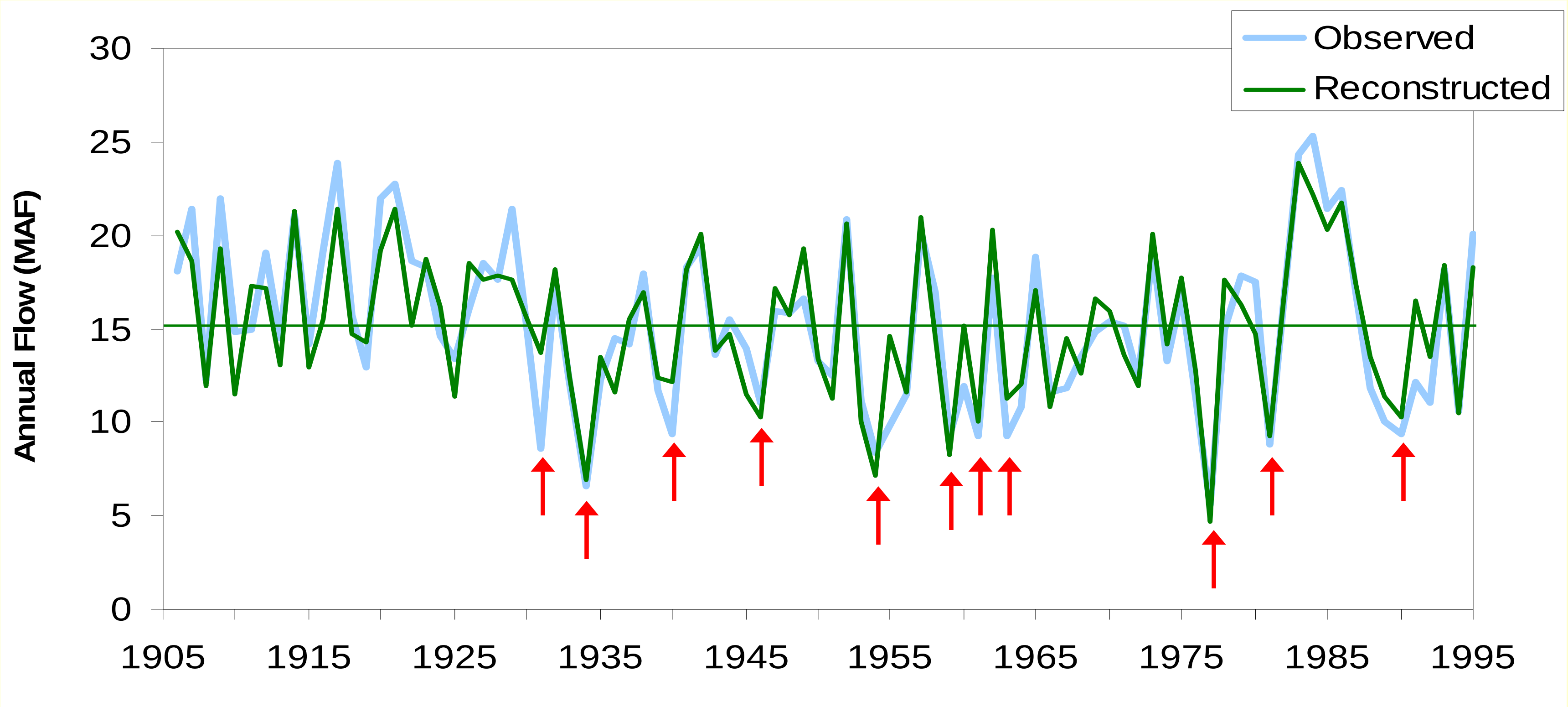
How does the reconstruction compare to the gage record?



	Observed	Recon'd
Mean	15.22	15.22
Max	25.27	23.91
Min	5.57	4.71
StDev	4.32	3.88
Skew	0.16	-0.14
Kurtosis	-0.58	-0.37
AC1	0.25	0.04

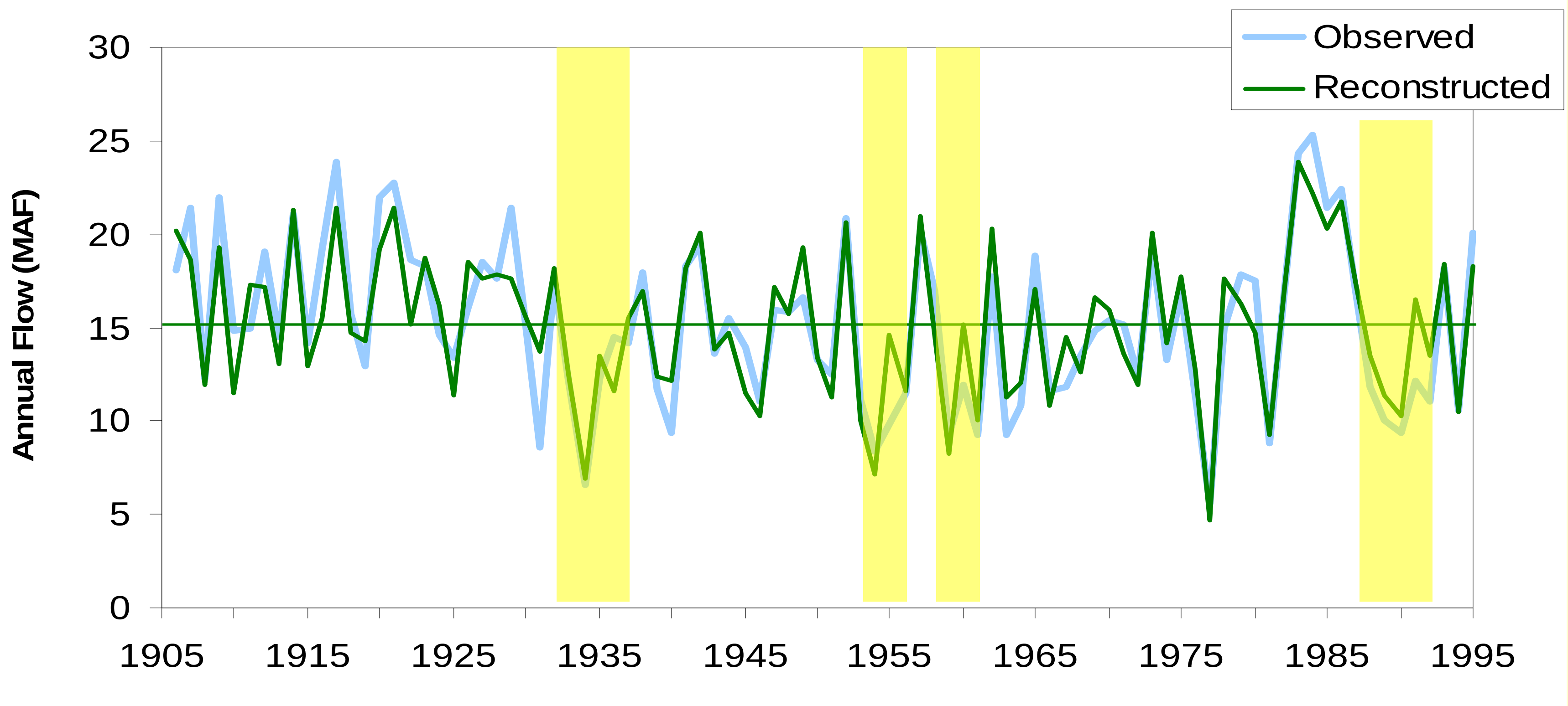
The means are the same, as expected from the the linear regression. Also as expected, the standard deviation in the reconstruction is lower than in the gage record, but in this reconstruction, the lowest flow value is slightly underestimated.

Subjective assessment of model quality



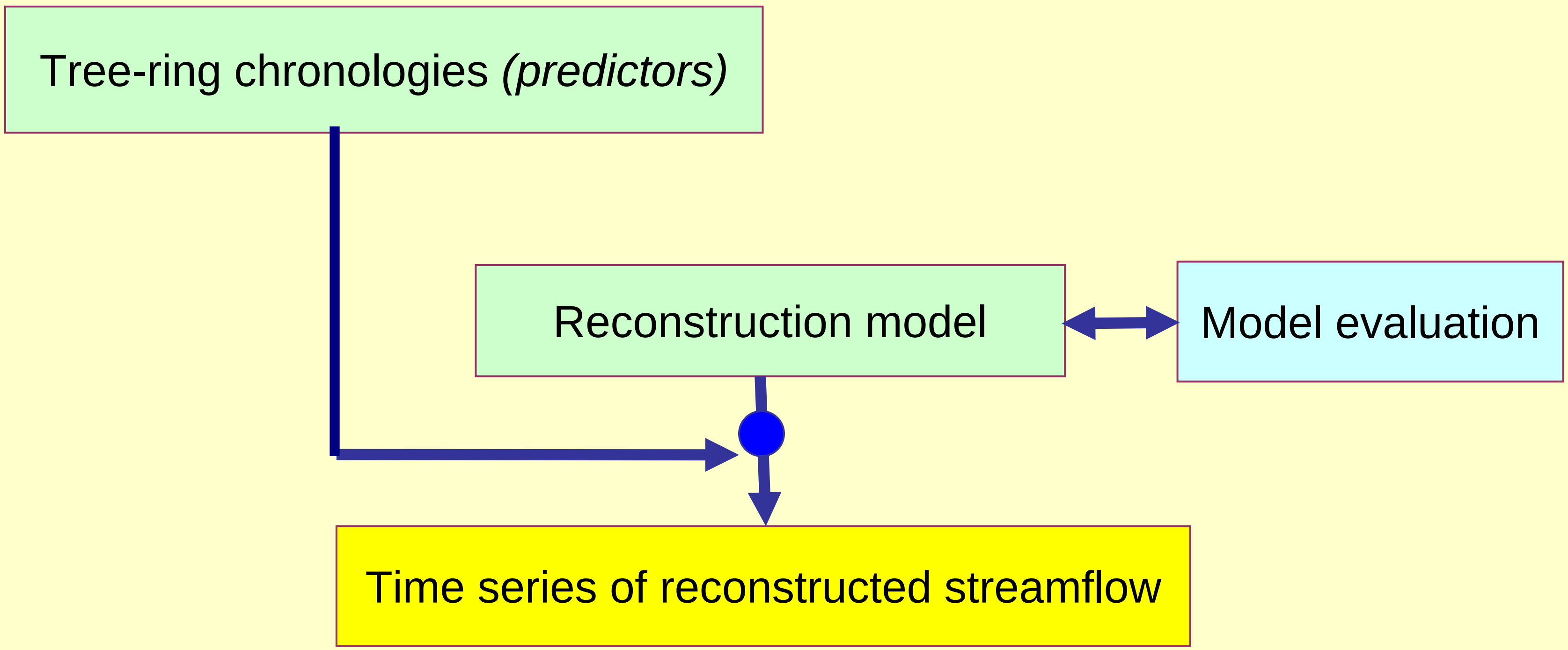
- Are severe drought years replicated well, or at least correctly classified as drought years?

Subjective assessment of model quality



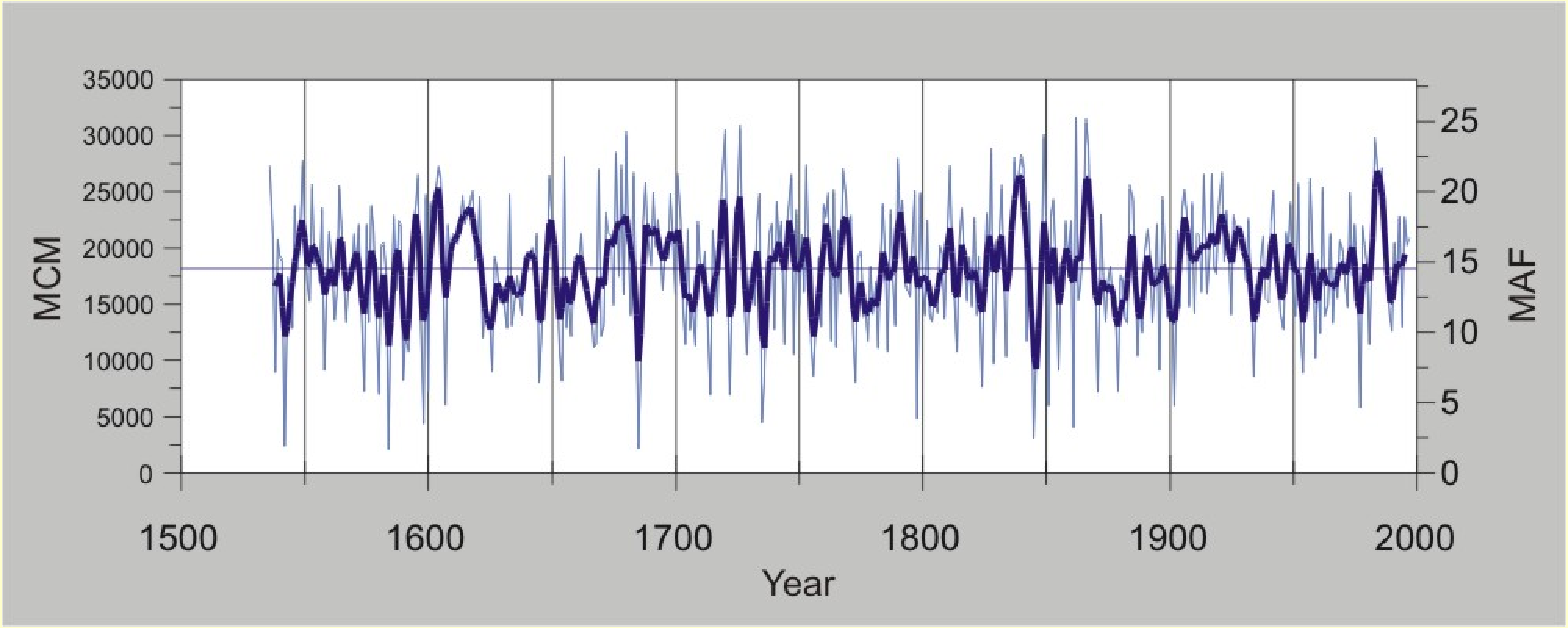
- Are the lengths and total deficits of multi-year droughts replicated reasonably well?

From model to full reconstruction



- When the regression model has been fully evaluated (residuals and validation statistics), then the model is applied to the full period of tree-ring data to generate the reconstruction

Full Lees Ferry Streamflow reconstruction, 1536-1997



Uncertainty in the reconstructions

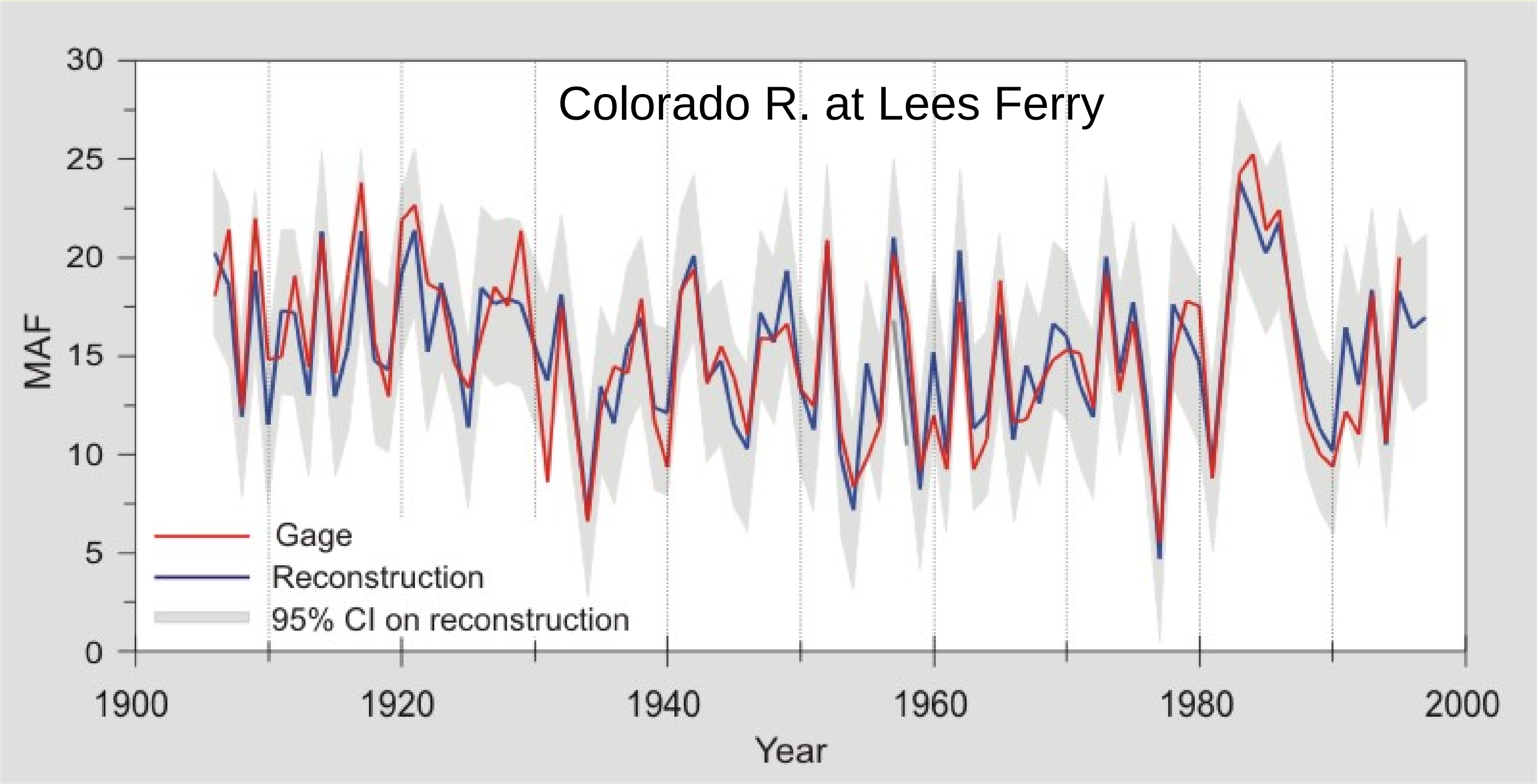
- Tree-ring data are imperfect recorders of climate and streamflow, so there will always be uncertainty in the reconstructed values

- The statistical uncertainty in the reconstruction model can be estimated from the validation errors (RMSE)

- RMSE only summarizes the uncertainty associated with a specific model, which is the result of many choices in the treatment of the data and development of the model

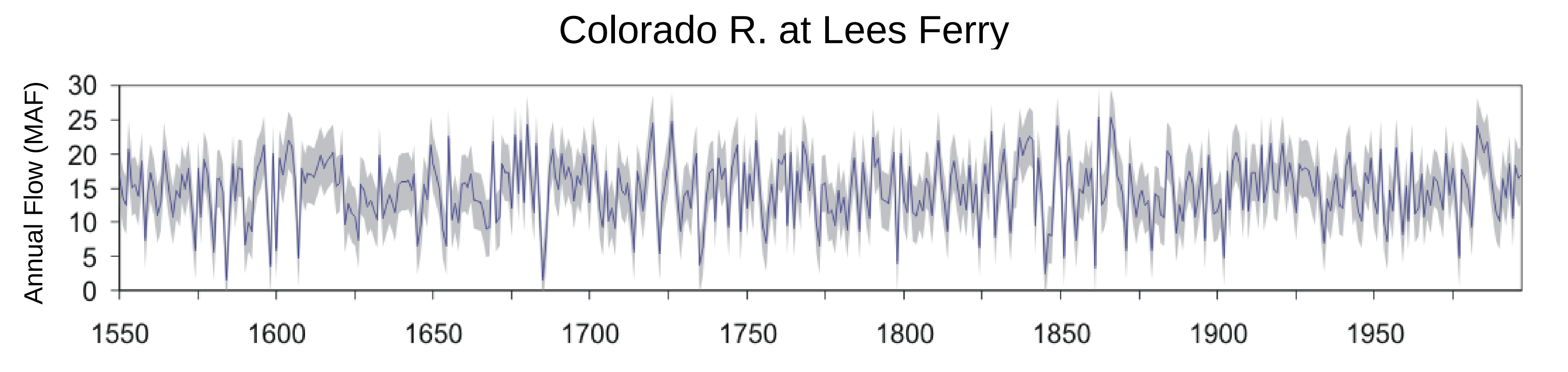
- The uncertainty associated with these data and modeling choices is not formally quantified but sensitivity analyses can help assess their impacts (e.g., set of chronologies, gage data/years used, modeling approach, treatment of data).

Using RMSE to generate confidence intervals for the model



- 2 x RMSE approximates the 95% confidence intervals around the reconstruction
- So the CIs should encompass ~95% of the gage values

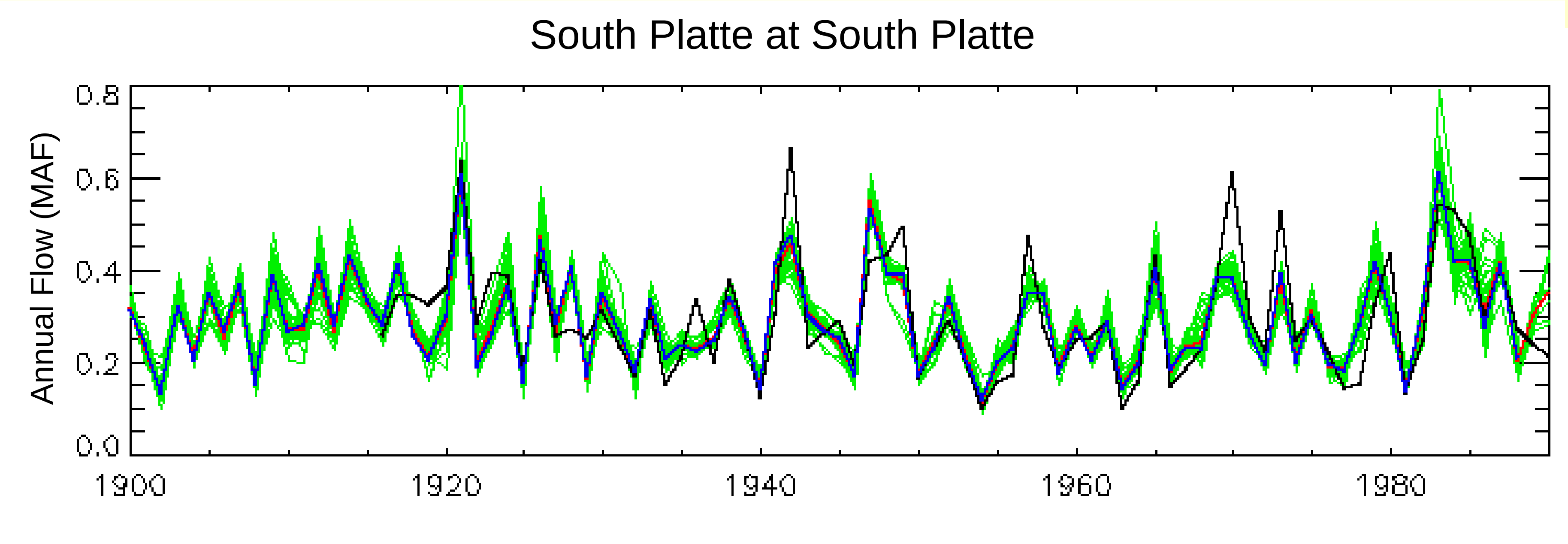
Using RMSE to generate confidence intervals



- In applying these confidence intervals to the full reconstruction, we implicitly assume that the RMSE is representative of uncertainty throughout the reconstruction

- Uniformitarian Principle: the the relationship between tree growth and climate does not change significantly over time

Sensitivity to calibration period

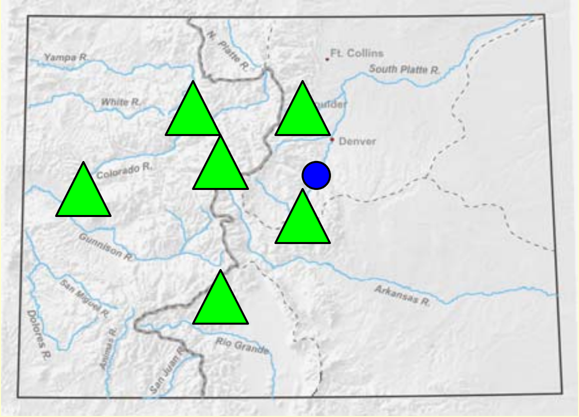


Calibration data ---
Single Model ---
Ensemble Mean ---
Ensemble Members ---

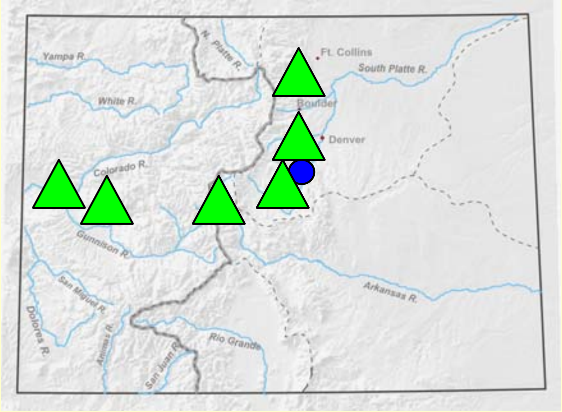
- Each of the 60 ensemble members is a model based on a different calibration period
- All members have similar sets of predictors

Sensitivity to chronologies used as predictors

- How sensitive is the reconstruction to the specific predictor chronologies in the pool and in the model?

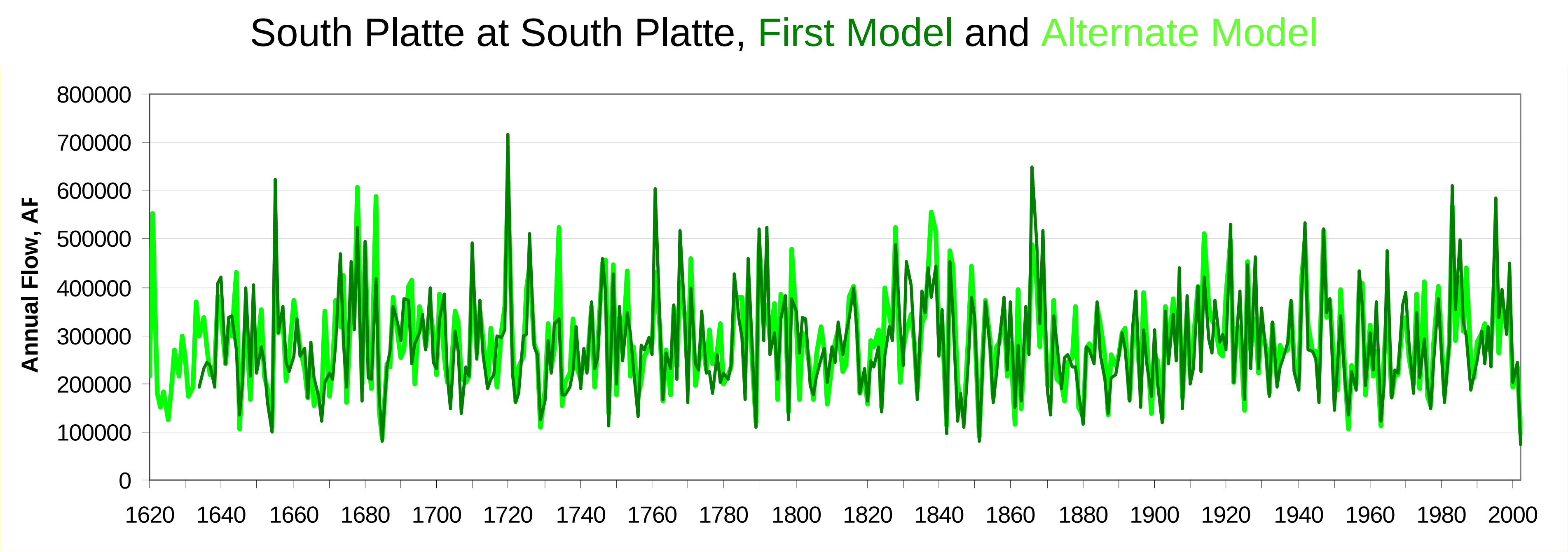


South Platte - First model



South Platte - Alternate model

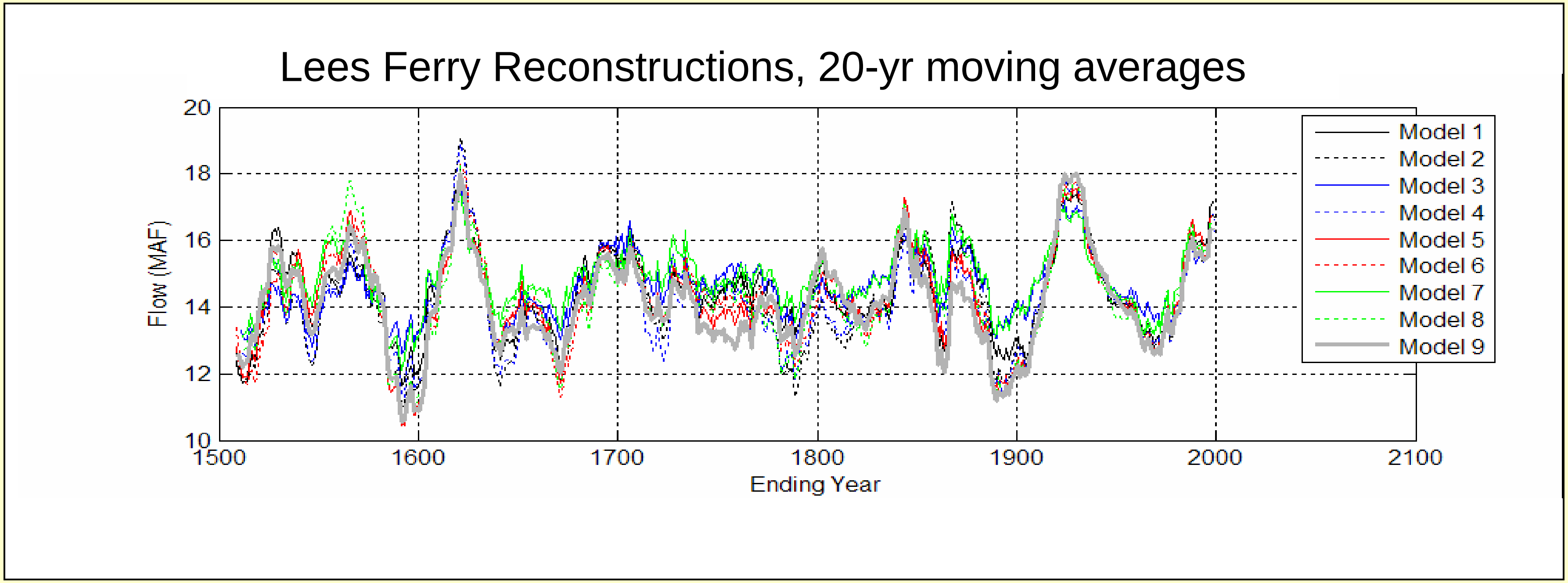
Sensitivity to available predictors - alternate models



- The two models correlate at r = 0.84 over their overlap period, 1634-2002
- *Completely independent sets of tree-ring data can result in very similar reconstructions*

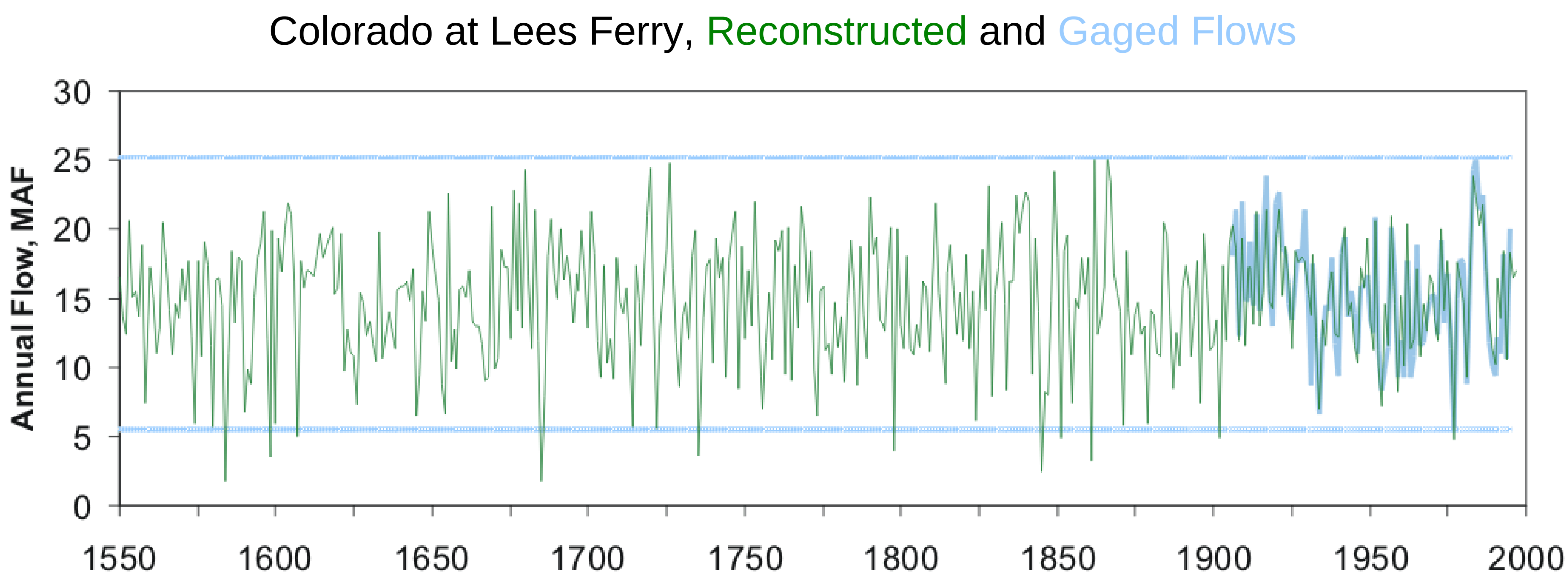
Sensitivity to other choices made in modeling process

Lees Reconstructions from 9 different models that vary according to chronology persistence, pool of predictors, model choice



Analysis from D. Meko

Uncertainty related to extreme values



- **Extremes of reconstructed flow not experienced in the calibration period often reflect tree-ring variations "beyond the range" of variations in the calibration period.**
- **As such, the estimates may be more uncertain than implied by the RMSE.**

Uncertainty in perspective

- RMSE is probably a reasonable measure of the magnitude of overall uncertainty in the reconstructions, but it should be recognized that it does not reflect all sources of uncertainty

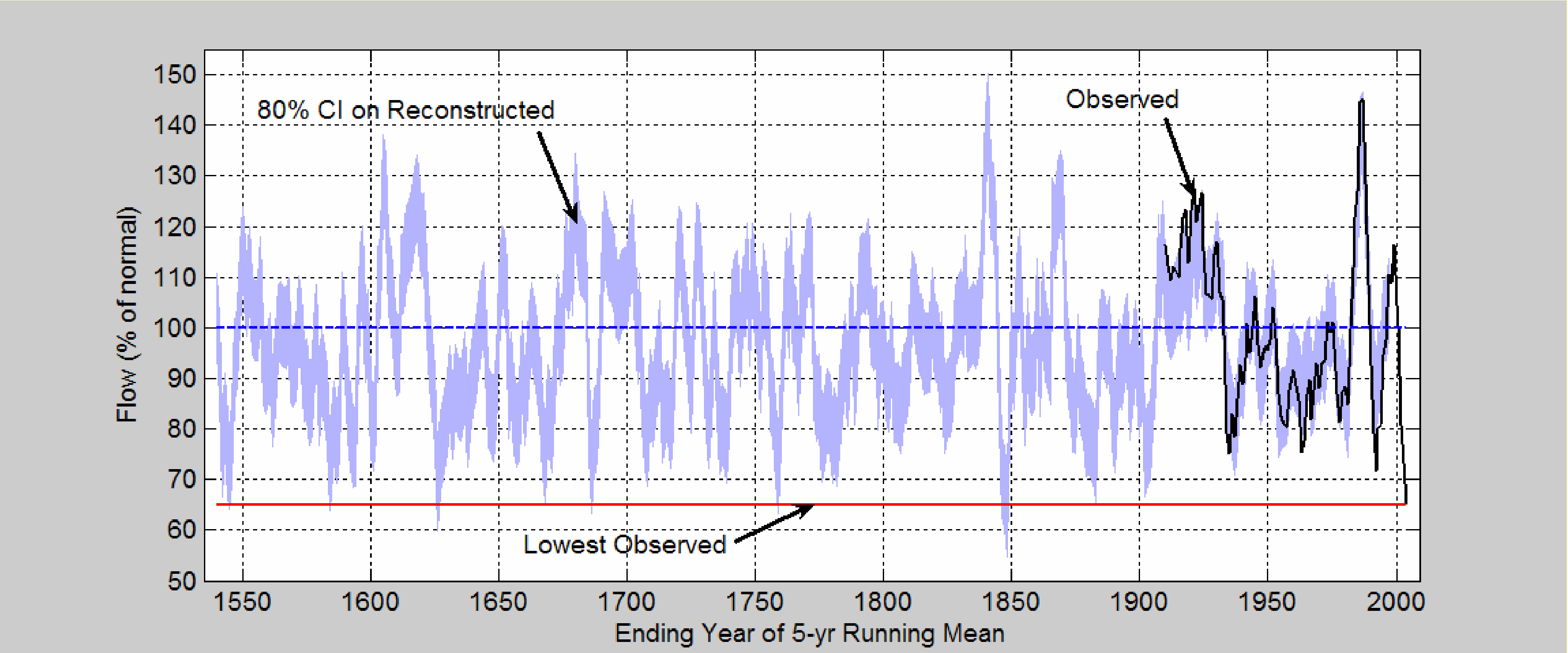
- Other alternative approaches are being generated, such as the noise added approach of Meko et al. 2001*

- There is usually no one reconstruction that is the “correct” one. A reconstruction is a plausible estimate of past hydroclimatic variability, and ensemble modeling shows that there can be a number of plausible reconstruction series.

Application of model uncertainty: using RMSE-derived confidence intervals in probabilistic drought analysis

Lees Ferry Reconstruction, 1536-1997
5-Year Running Mean

Assessing the 2000-2004 drought in a multi-century context



Data analysis: Dave Meko

Where to find reconstruction data

TreeFlow web site for Colorado

and soon to include:

• other gages in the Upper Colorado River basin

• Lower Colorado River basin gage reconstructions

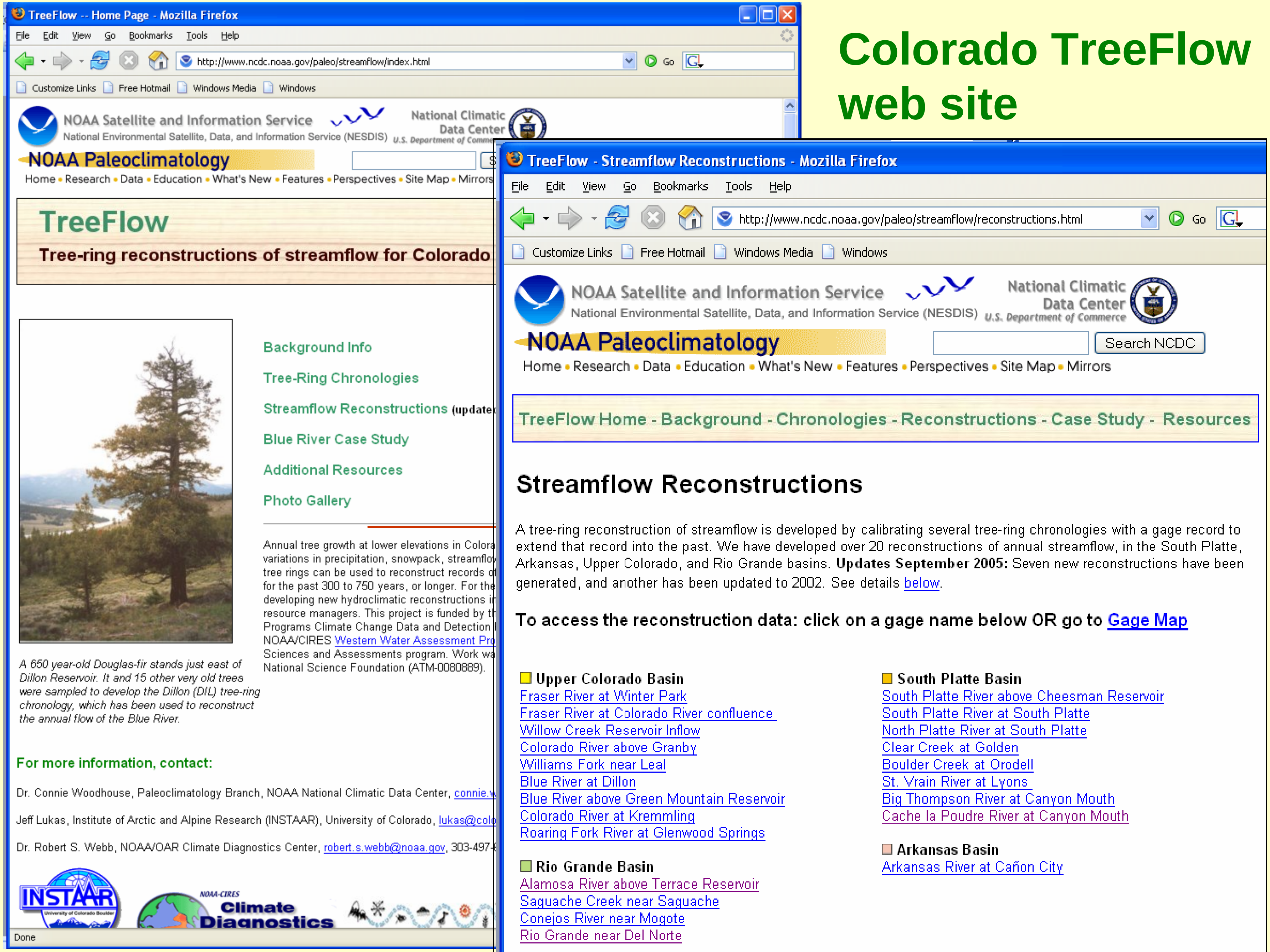
• California gage reconstructions

Until then

• **UA/Salt River Project** collaboration

• **World Data Center for Paleoclimatology** reconstructions

Colorado TreeFlow web site



www.ncdc.noaa.gov/paleo/streamflow

Lower Colorado River basin gage reconstructions

Synchronous Extreme Streamflows, Upper Colorado and Salt-Verde Basins

- Salt + Verde + Tonto
- Gila at head of Safford Valley
- Salt + Tonto
- Verde

A Collaborative Project between The University of Arizona's Laboratory of Tree-Ring Research & The Salt River Project

http://fpnew.ccit.arizona.edu/kkh/srp.htm**, see full report**

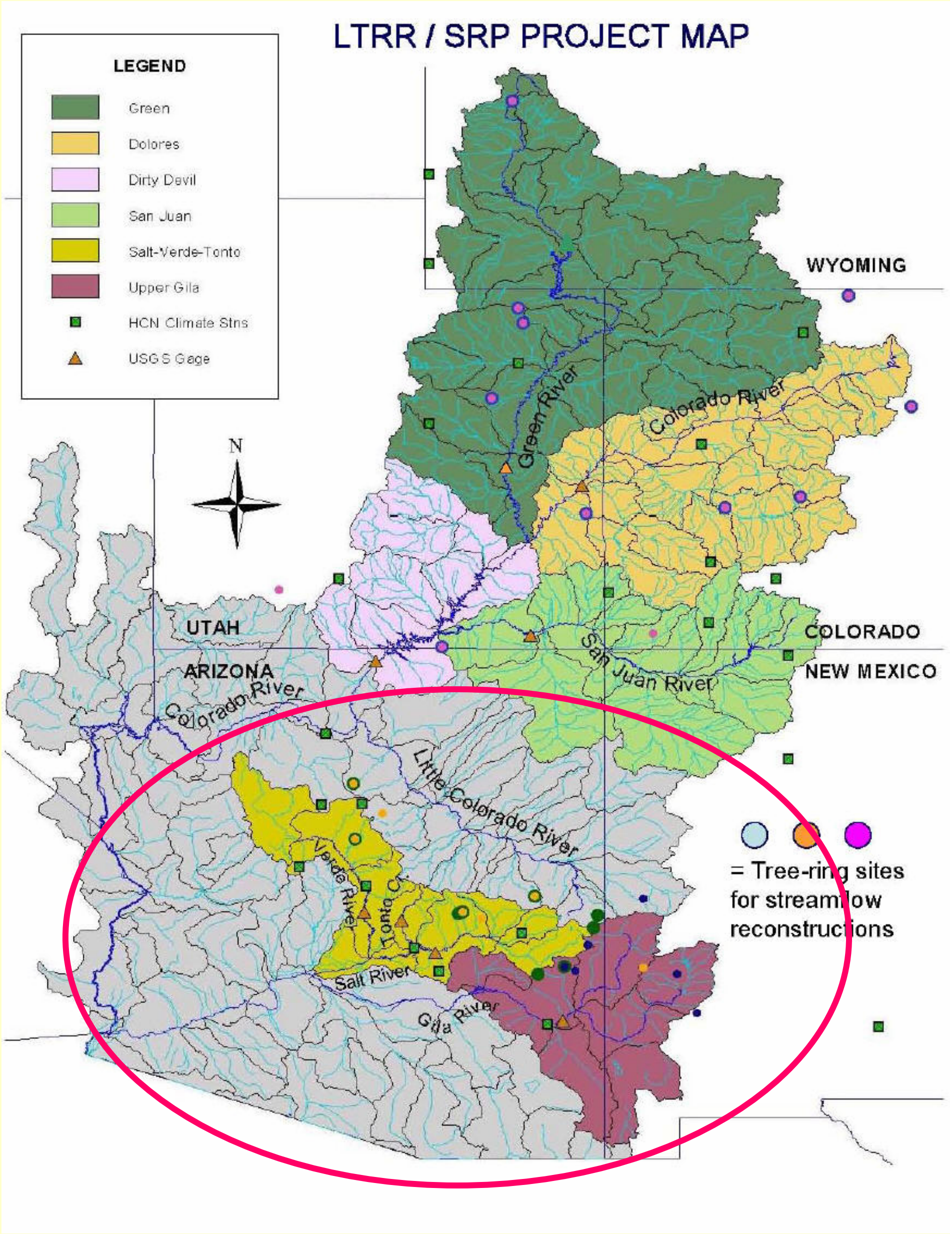


Image courtesy of K. Hirschboeck and D. Meko (U. AZ)

Other streamflow reconstructions in the Upper Colorado River basin and elsewhere

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
U.S. Department of Commerce

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Updated Streamflow Reconstructions for the Upper Colorado River Basin

Updated Streamflow Reconstructions for the Upper Colorado River Basin
Water Resources Research
Vol. 42, W05415, 11 May 2006.

Connie A. Woodhouse[1], Stephen T. Gray[2], David M. Meko[3]

[1] NOAA National Climatic Data Center, Boulder, CO
[2] U.S. Geological Survey, Desert Laboratory, Tucson, AZ
[3] Laboratory of Tree-Ring Research, University of Arizona, Tucson AZ

Satellite image of Lake Powell, Utah on the Colorado River above Lee's Ferry, Arizona. USGS Landsat Photo.

ABSTRACT:
Updated proxy reconstructions of water year (October-September) streamflow for four key gauges in the Upper Colorado River Basin were generated using an expanded tree ring network and longer calibration records than in previous efforts. Reconstructed gauges include the Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona. The reconstructions explain 72-81% of the variance in the gauge records, and results are robust across several reconstruction approaches. Time series plots as well as results of cross-spectral analysis indicate strong spatial coherence in runoff variations across the subbasins. The Lees Ferry reconstruction suggests a higher long-term mean than previous reconstructions but strongly supports earlier findings that Colorado River allocations were based on one of the wettest periods in the past 5 centuries and that droughts more severe than any 20th to 21st century event occurred in the past.

Download data from the WDC Paleo archive:
Upper Colorado Streamflow Reconstructions in Text or Microsoft Excel format.
Supplementary Data 1. Chronology data and metadata
Supplementary Data 2. Regression equations and coefficients, PC data
Supplementary Data 3. Loadings from PCA on chronologies

To read or view the full study, please visit the AGU website.
It was published in **Water Resources Research**, Vol. 42, W05415, 11 May 2006.

http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
U.S. Department of Commerce

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Climate Reconstructions

The NOAA Paleoclimatology Program archives reconstructions of past climatic conditions derived from paleoclimate proxies, in addition to the Program's large holdings of primary paleoclimatic proxy data. Included are reconstructions of past temperature, precipitation, vegetation, streamflow, sea surface temperature, and other climatic or climate-dependent conditions.

Please Cite Data Contributors!

Reconstructions: Air Temperature | Hydroclimate | Circulation | SST | Other | Search by Author

Streamflow

Asia
Selenge River, Mongolia Streamflow, 360 Years, Davi et al. 2006.

Australia, New Zealand
Burdekin River, Australia Streamflow, 350 Years, Isdale et al. 1998.

North America
Colorado River and tributaries flow, Text or Microsoft Excel format, 500 Years, Stockton and Jacoby 1976.
Upper Colorado River and tributaries flow, Text or Microsoft Excel format, 500 Years, Woodhouse et al. 2006.
Sacramento River, California flow reconstruction, 1109 Years, Meko et al. 2001.
Yellowstone River, Montana flow reconstruction, 270 Years, Graumlich et al. 2003.
TreeFlow Project - Tree Ring Reconstructions of Streamflow for Colorado
Clear Creek Colorado Annual Flow Reconstruction, 300 Years, Woodhouse 2000.
Middle Boulder Creek Colorado Flow Reconstruction, 280 Years, Woodhouse 2001.
White River, Arkansas flow reconstruction, 963 Years, Cleaveland 2000.
White River, Arkansas flow reconstruction, 280 Years, Cleaveland and Stahle 1989.

World Data Center for Paleoclimatology
http://www.ncdc.noaa.gov/paleo/recons.html

Winnipeg River Basin drought

- 20 new moisture-sensitive chronologies collected in 2004-2005 (green and black symbols)

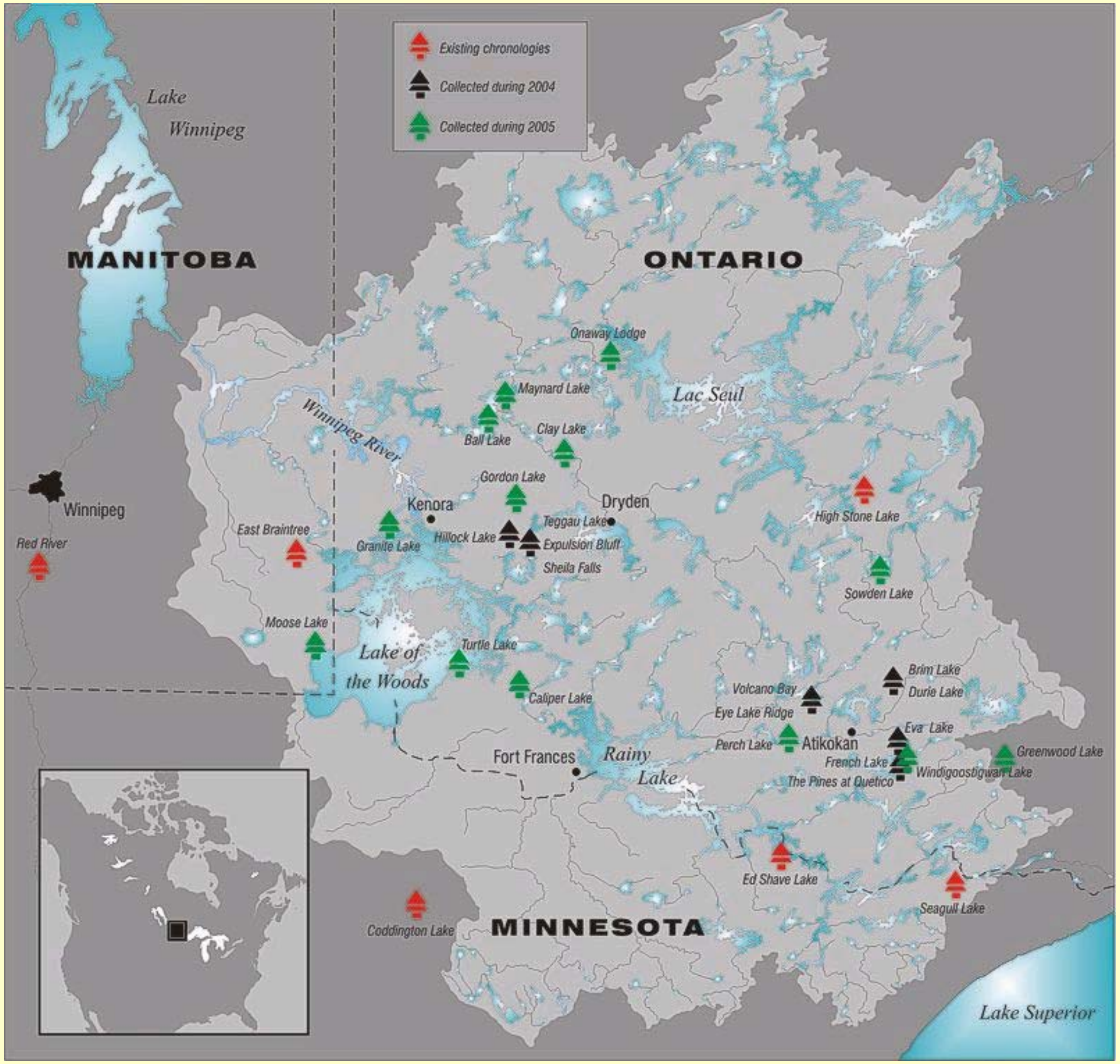


Image courtesy of S. St. George (CGS, U. AZ)

Analysis of streamflow reconstructions

- How representative is the gage record of the full reconstruction period?
- Examining streamflow characteristics in a long-term context

Relevance to future planning in light of climate change

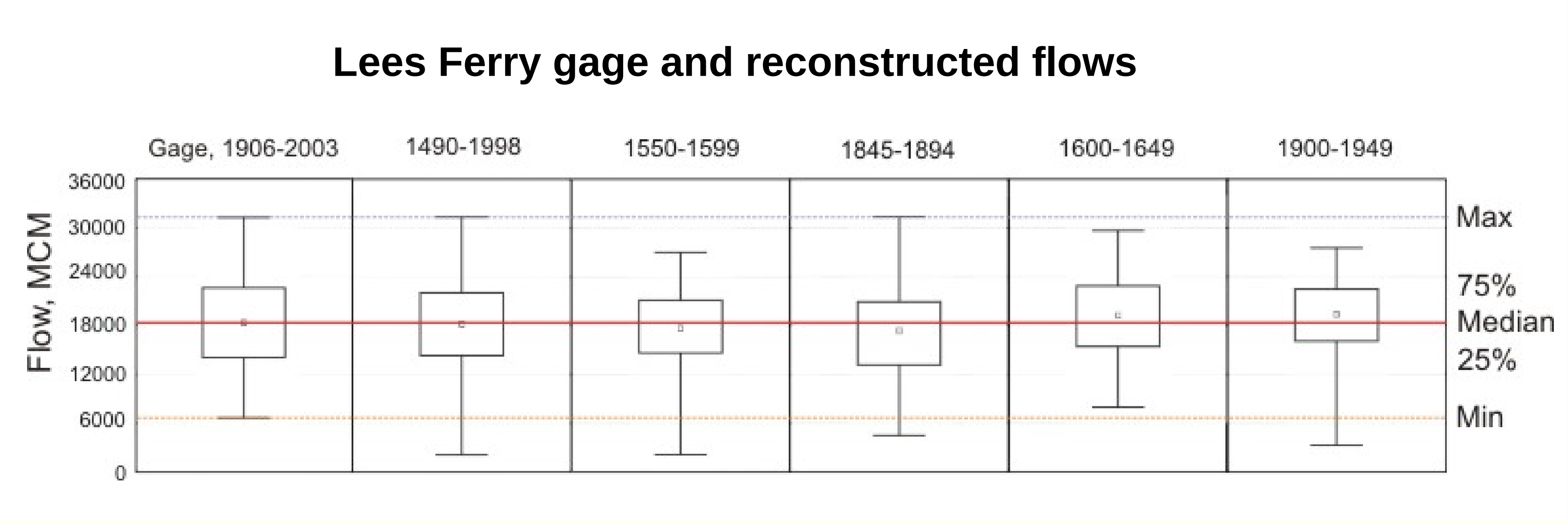
- How is the climate changing? How can records of the past be useful in this context?

Applications to drought and water resource management

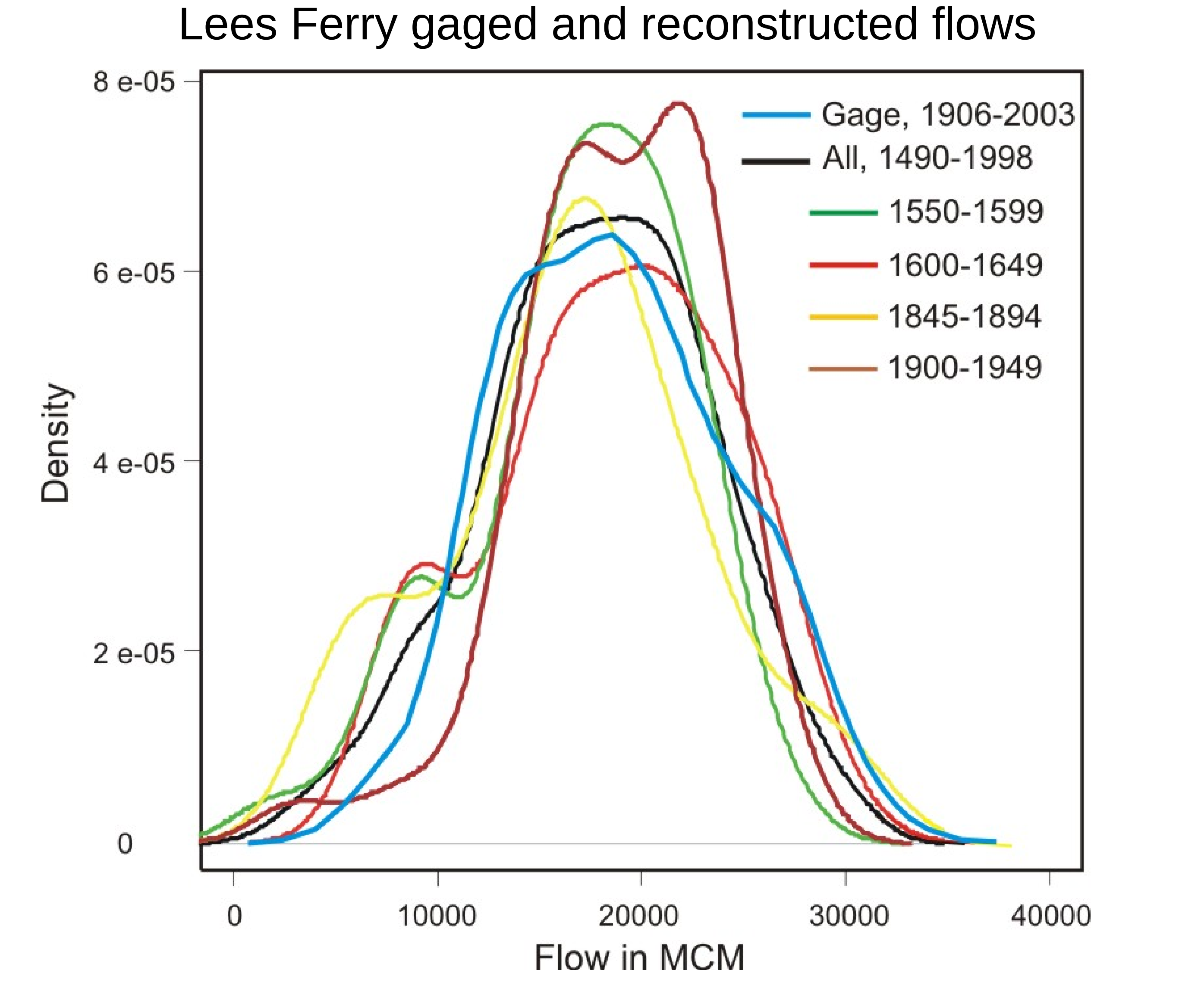
- Drought planning and paleoclimatology (Gregg Garfin)
- Presentations from SRP, USBR, and Manitoba Hydro
- Discussion

Analysis of streamflow reconstructions

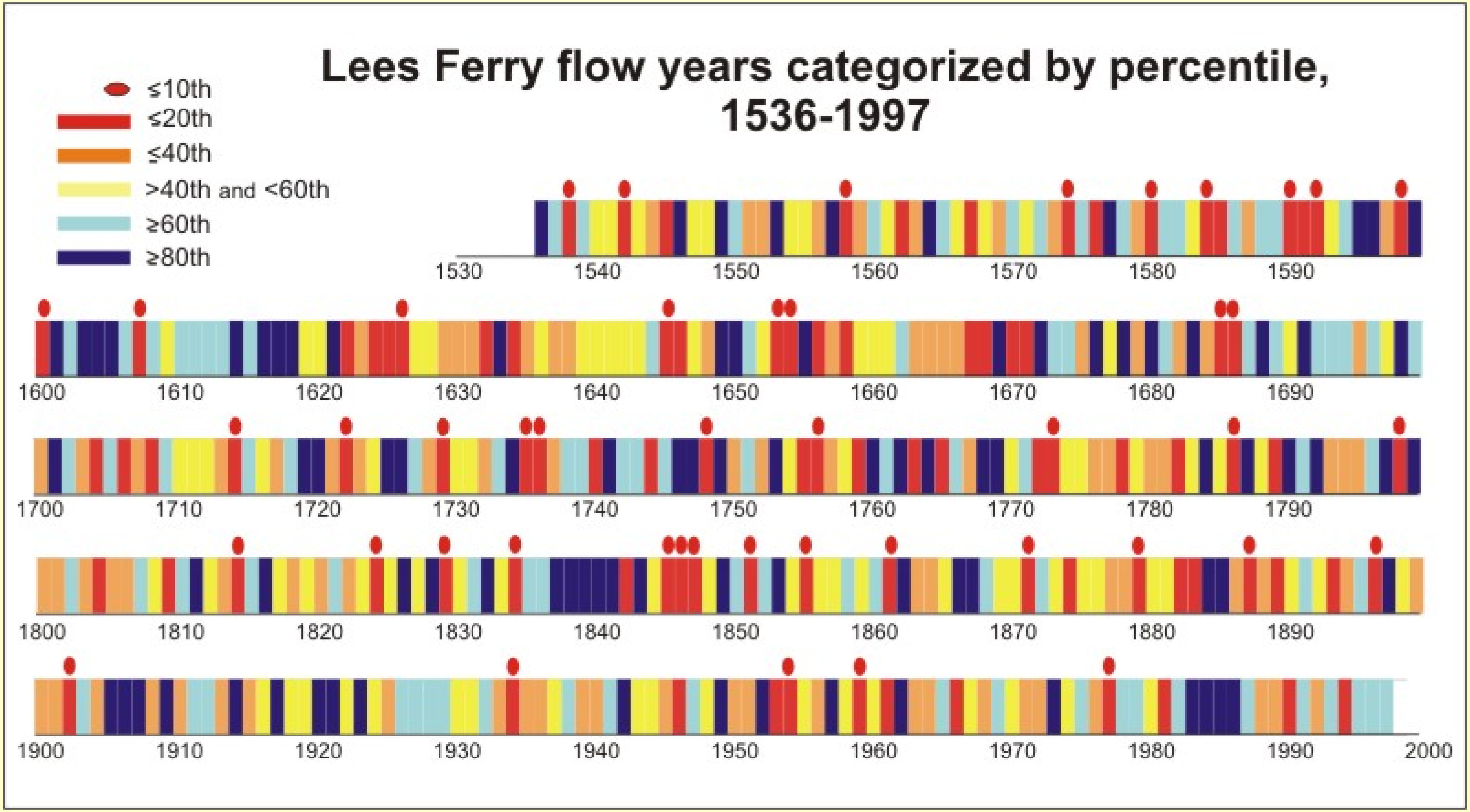
Box and whiskers plots can be used to highlight comparisons between the gage and reconstructed flow records



Probability density functions (PDFs) for gage, reconstruction and subsets of reconstructed flows show the differences in the distribution of values

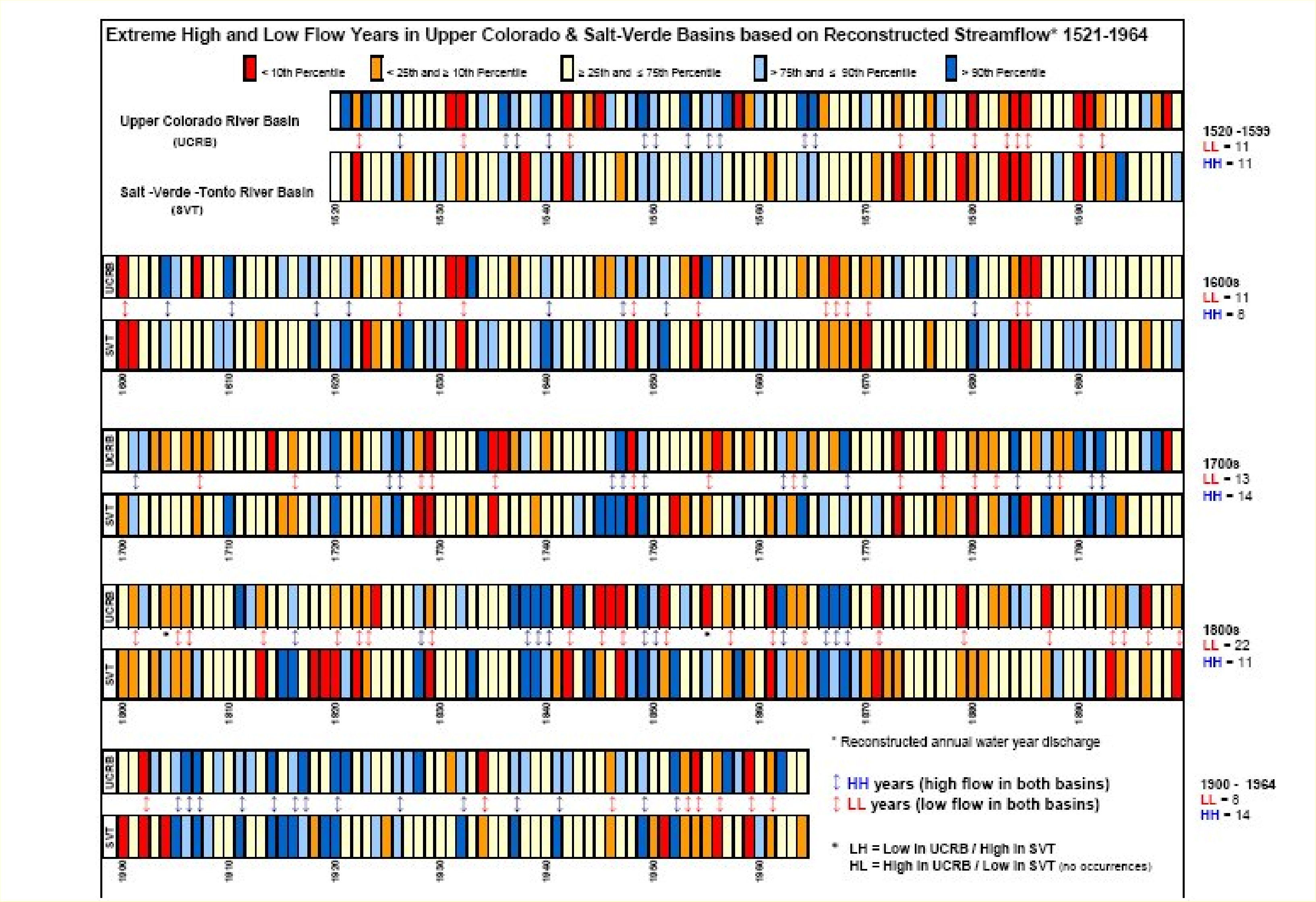


The temporal distribution or sequences of high and low flow years can also be examined

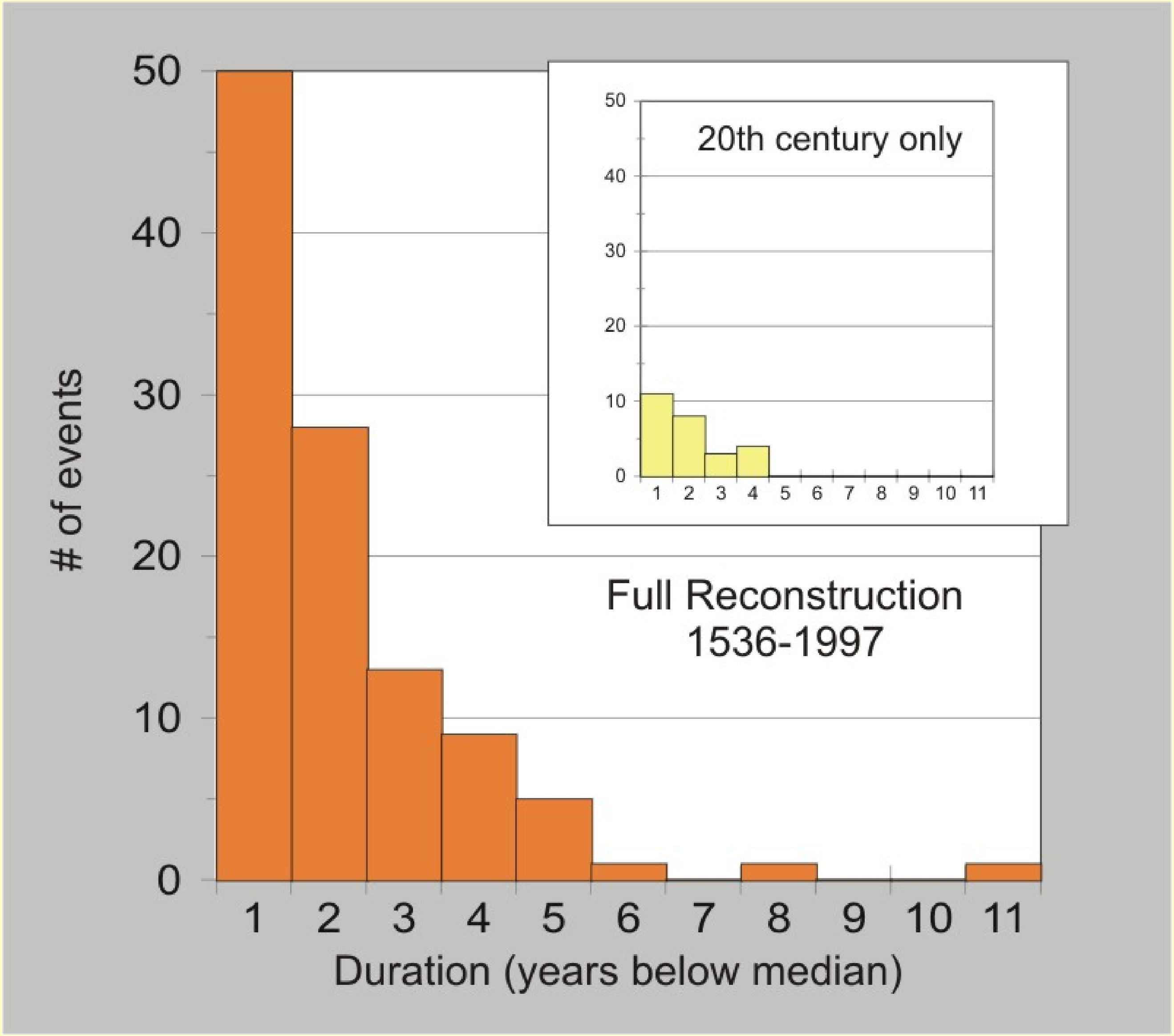


Extreme events are not evenly distributed over time!

Extreme flow events can also be assessed across different watersheds, here the Upper Colorado and Salt-Verde River basins.



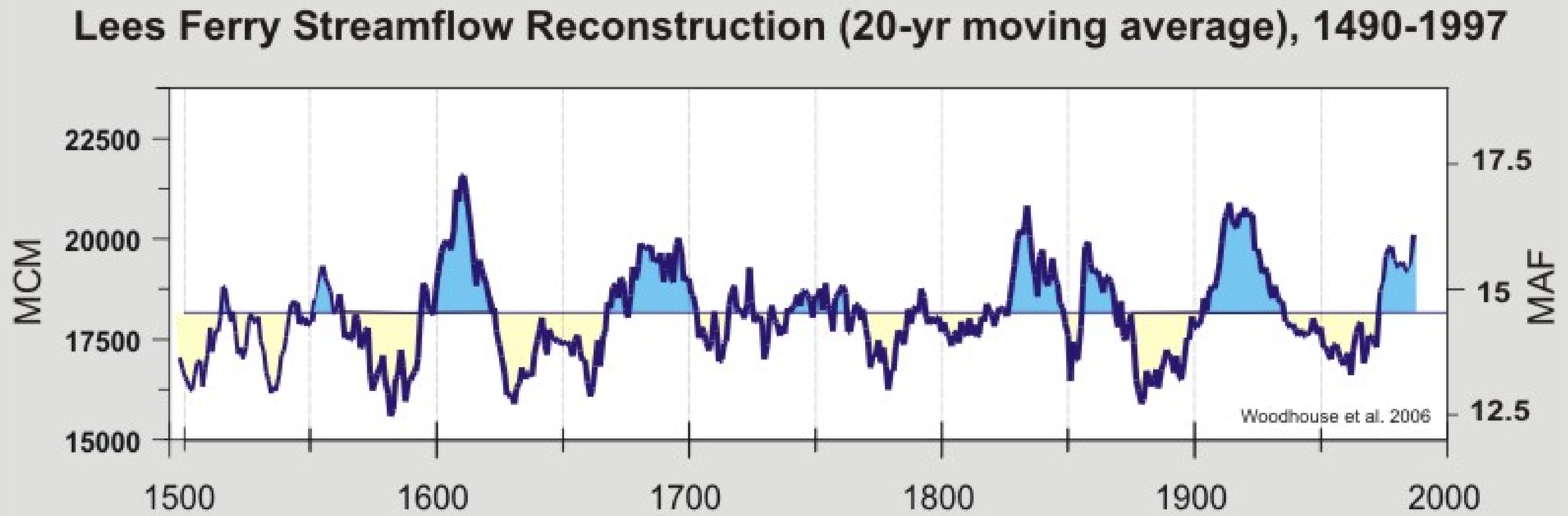
Reconstructed Lees Ferry Streamflow, 1536-1997
Drought Duration and Frequency of Drought Events



Here, drought is defined as one or more consecutive years below the long-term median.

The 20th century represents only a subset of the droughts in the full reconstruction period.

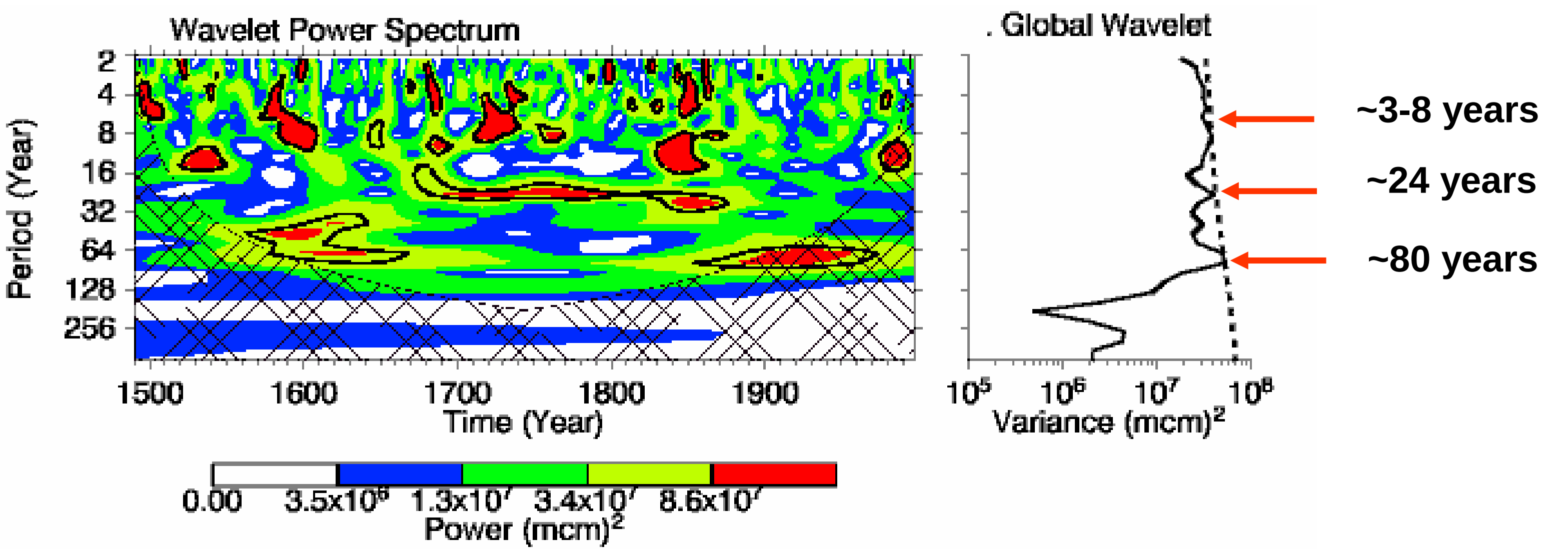
Decadal-scale variability is evident. A question currently being addressed by the scientific community is: What drives this variability?



Pluvials Wettest non-overlapping 20-yr average	Droughts Driest non-overlapping 20-yr average
1602-1621	**1573-1592**
1905-1924	**1622-1641**
1825-1844	**1870-1889**
1978-1997	**1652-1671**
1687-1706	**1526-1545**
	1953-1972 (8th)

Slow variations in oceans temperatures interact with the atmosphere to cause changes in circulation features related to drought and wet periods.

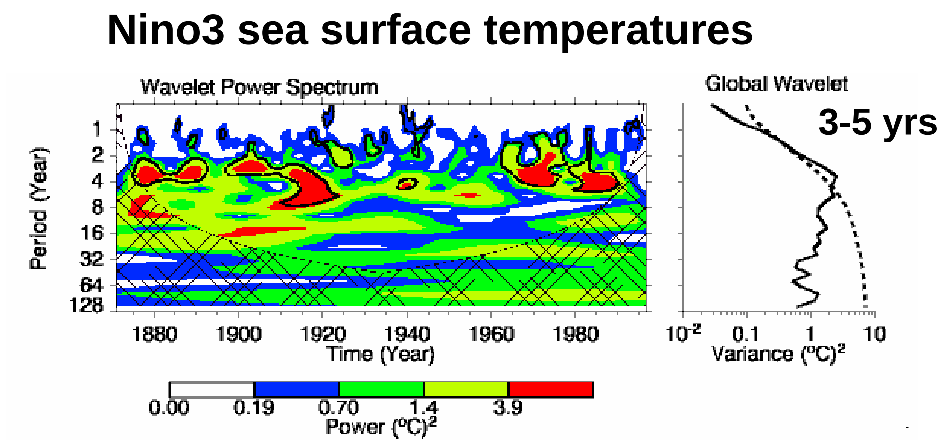
Lees Ferry streamflow reconstruction, 1490-1997

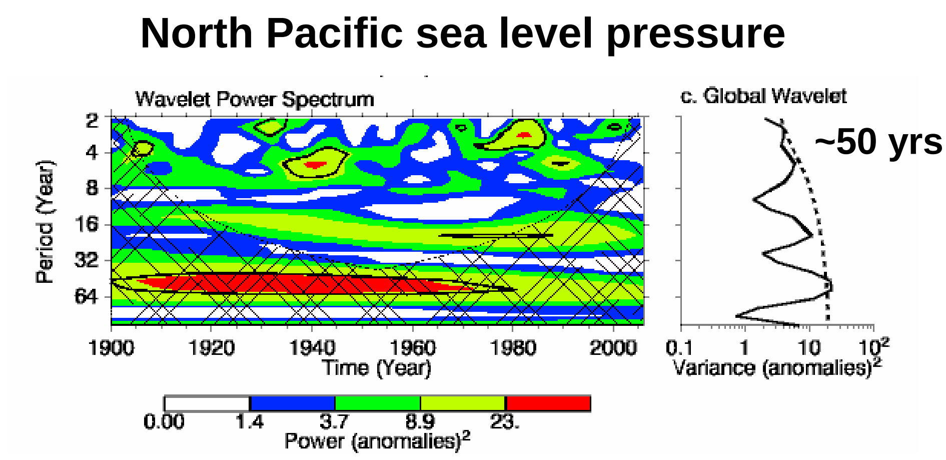


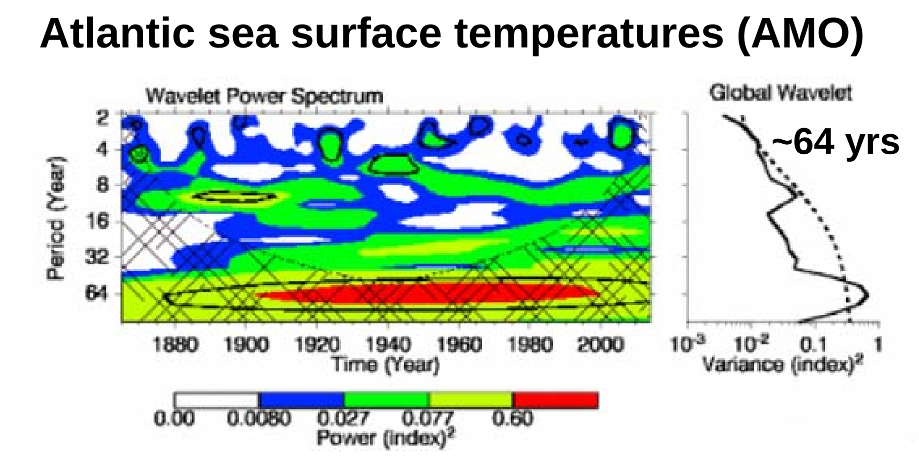
Wavelet power spectrum: Black contour is the 10% significance level.
The global wavelet power spectrum: The dashed line is the 10% significance level.

http://atoc.colorado.edu/research/wavelets/

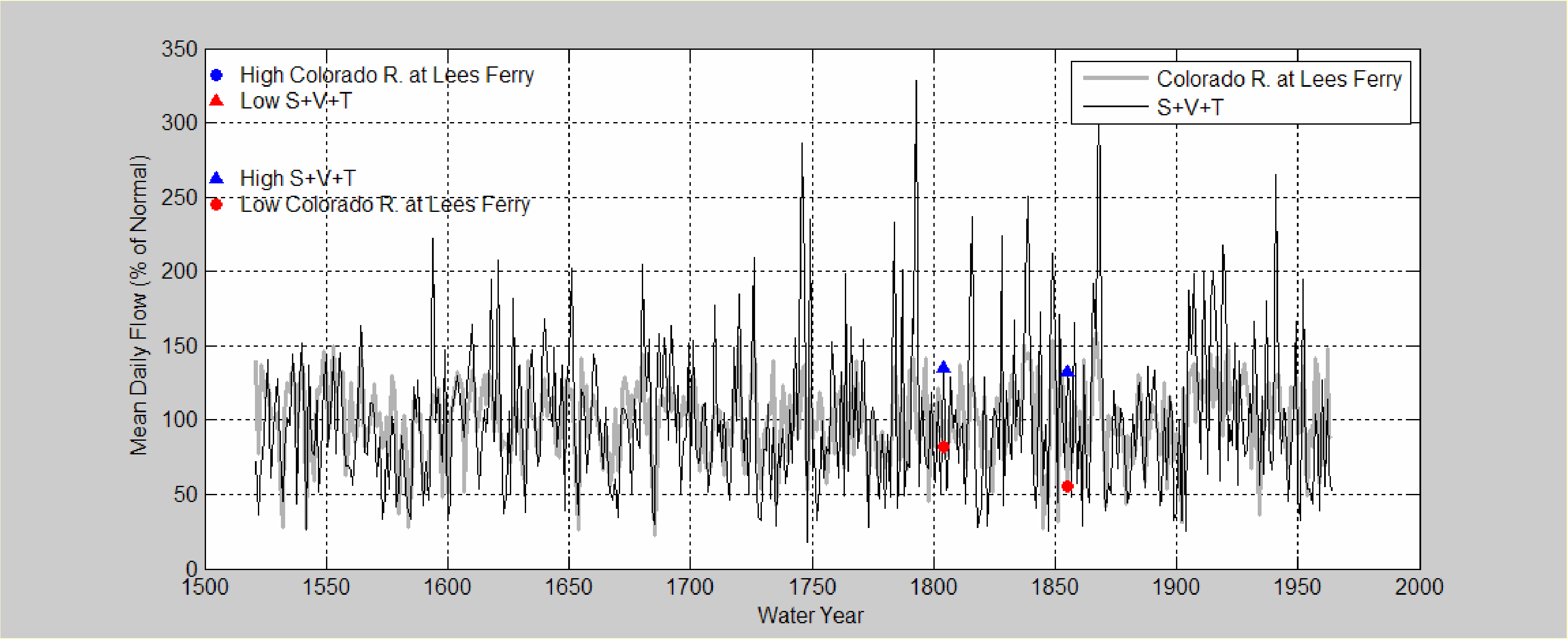
Ocean/atmosphere features operate at a number of time scales; determining their relationship with western US climate is a current topic of research.







Upper Colorado and Salt/Verde/Tonto Reconstructed Flows



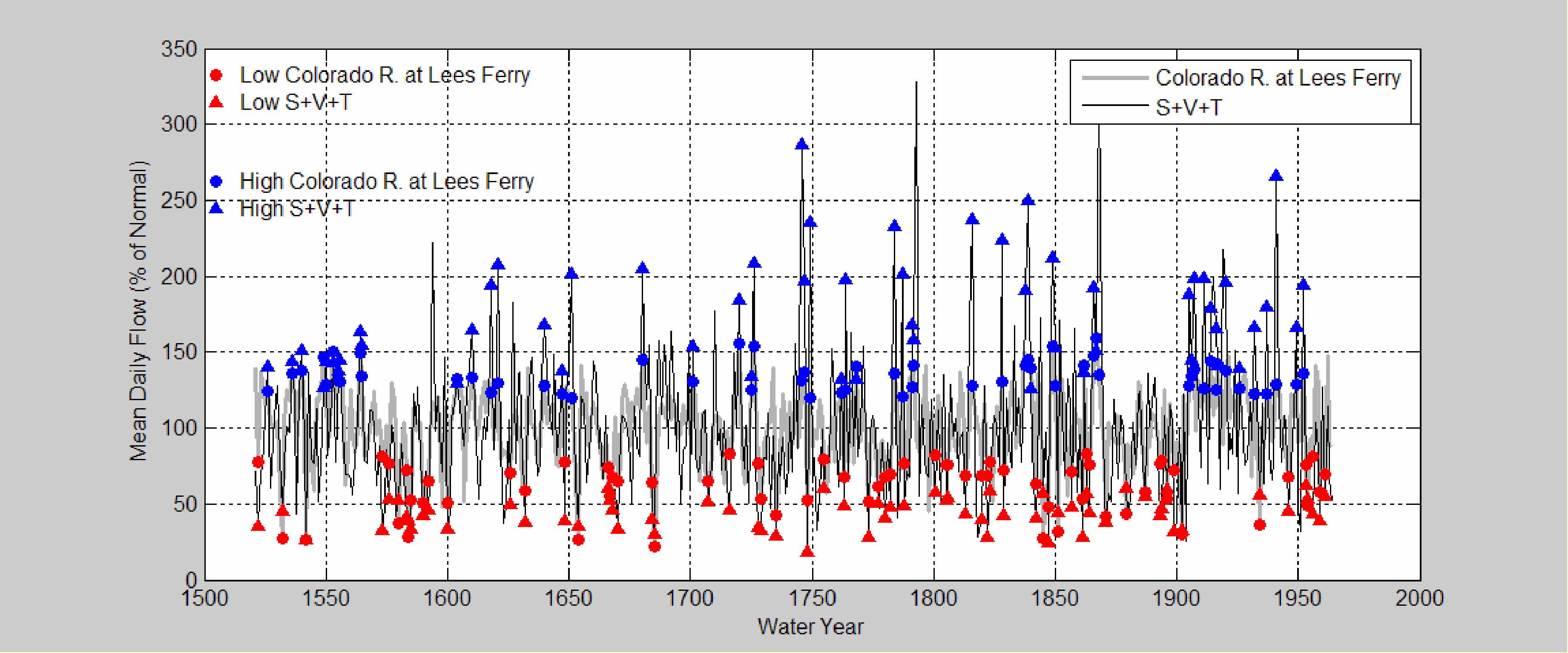
Thresholds for low (L) and high (H) flow events are defined by 25th and 75th percentiles of annual flows

Probability (HL) = 0 / 444 = 0

Probability (LH) = 67 / 444 = 0.004

From Hirschboeck and Meko, SRP report

Upper Colorado and Salt/Verde/Tonto Reconstructed Flows



Probability (HH) = 57 / 444 = 0.128

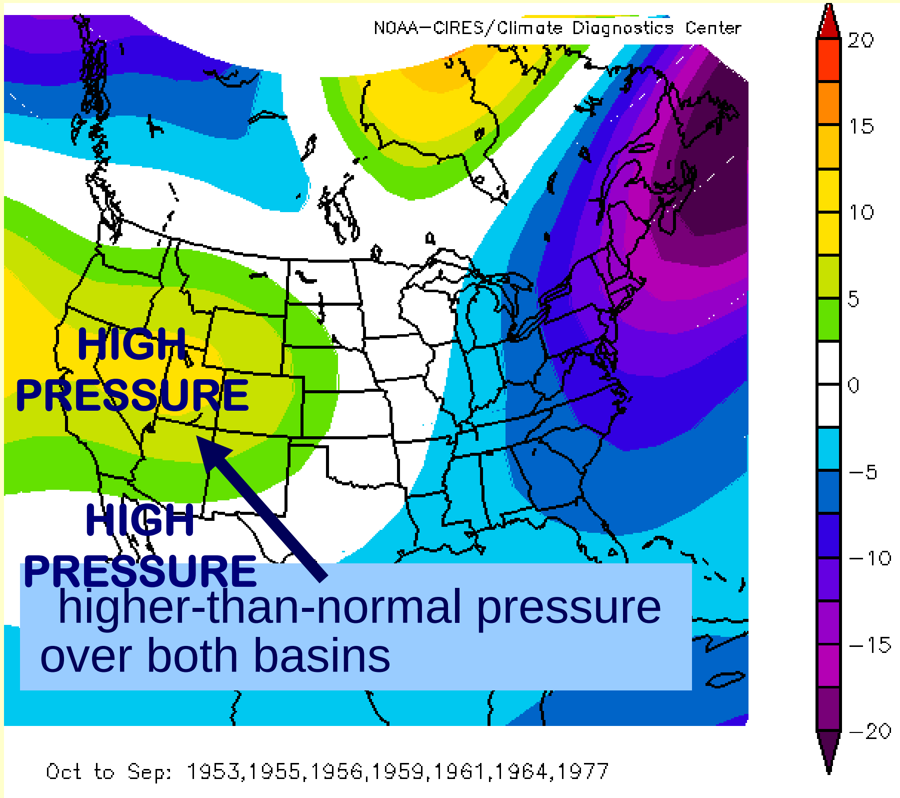
Probability (LL) = 66 / 444 = 0.149

From Hirschboeck and Meko, SRP report

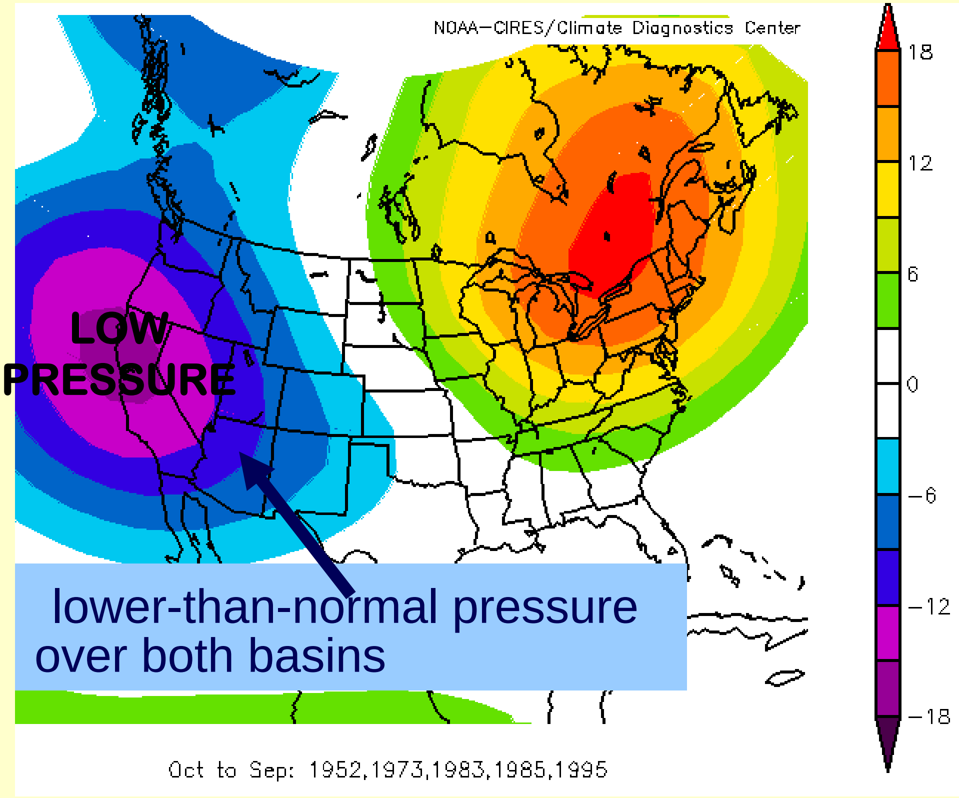
Climate during concurrent (upper and lower Colorado basins) high or low flow years

500 mb Height Anomalies
(LL and HH years from observed flows)

LL WATER YEARS

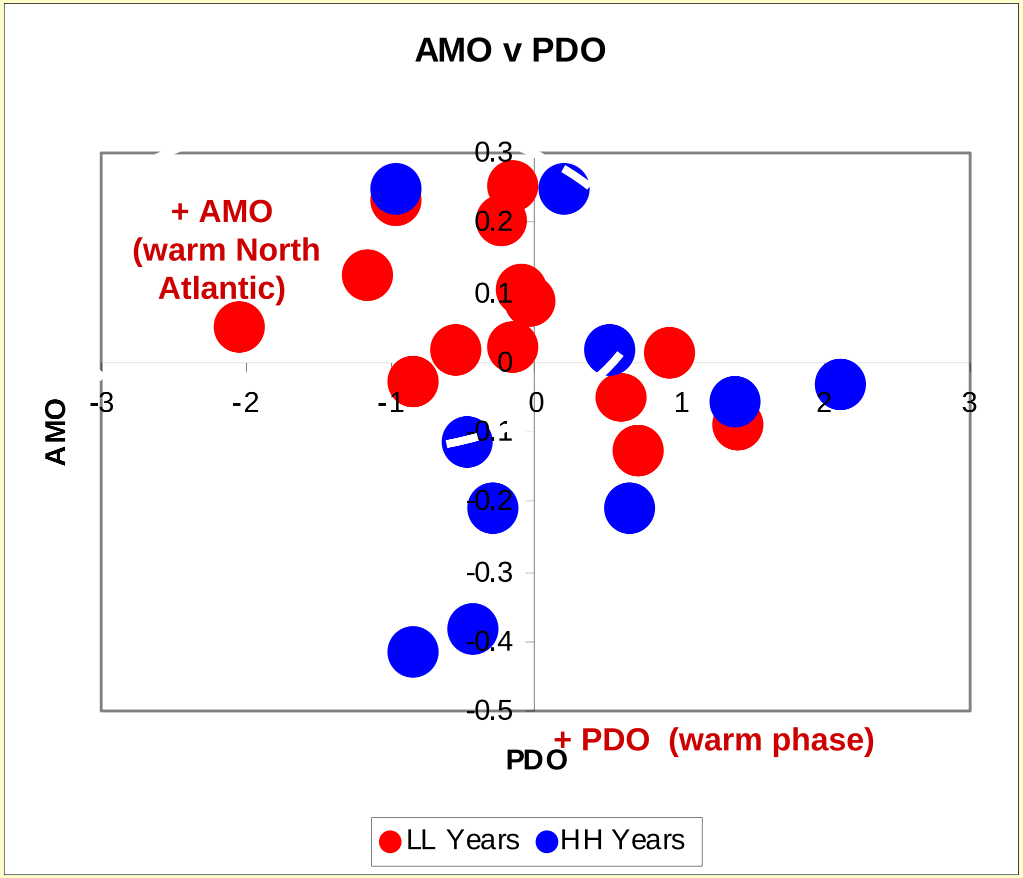


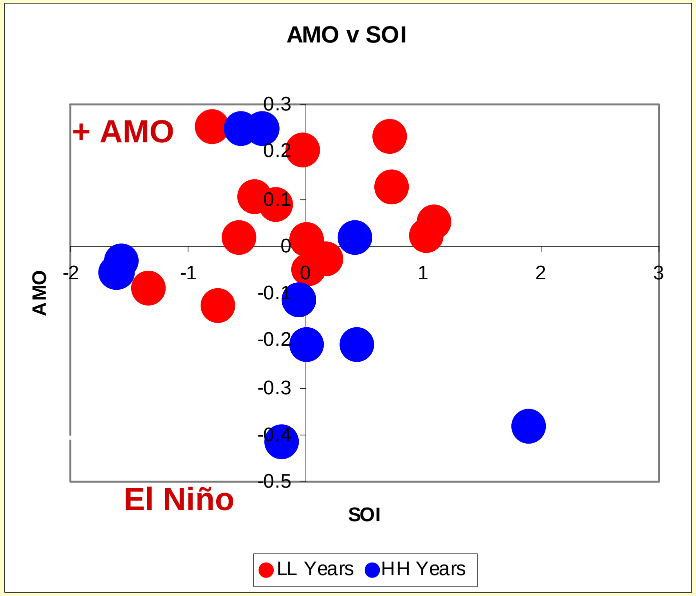
HH WATER YEARS



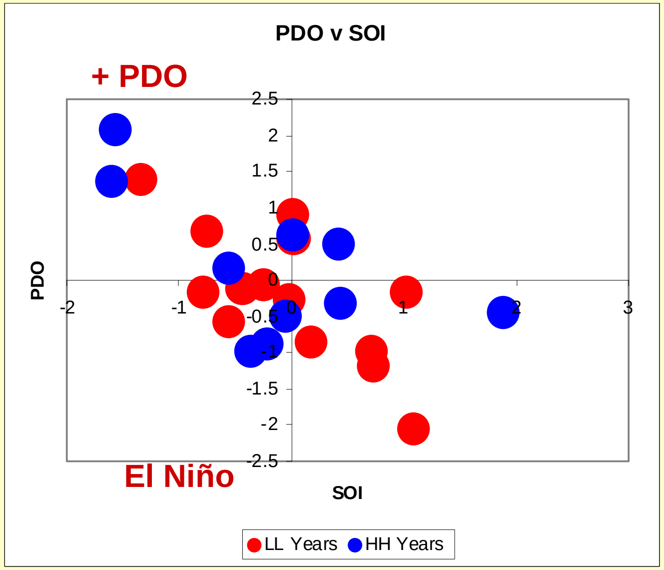
500 mb Geopotential Height (m) Composite Anomaly, Oct-Sep water year

Link to Sea Surface Temperature Indices?



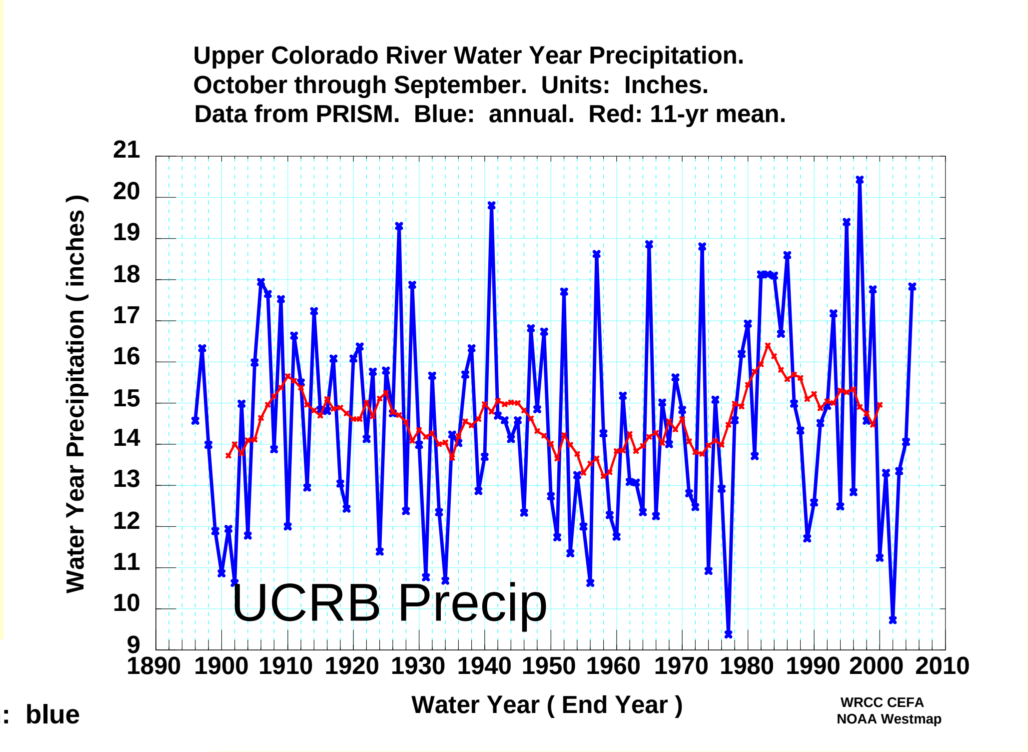


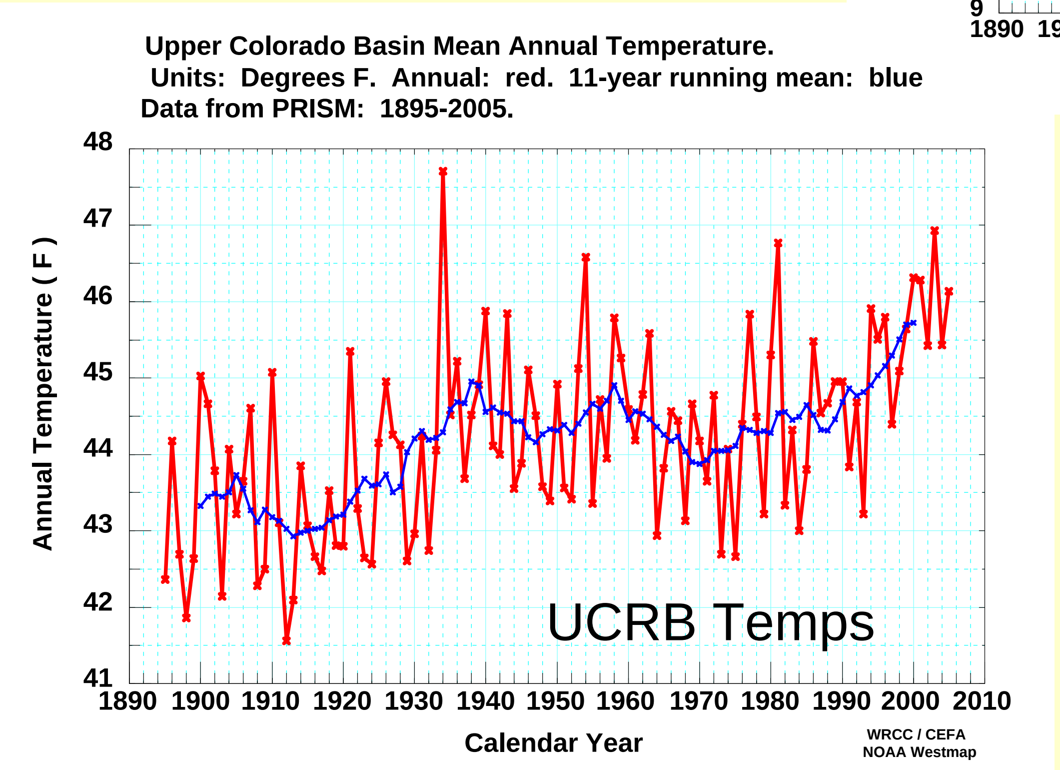
Relationships less clear w/ other indices



From Hirschboeck and Meko, SRP report

How relevant is the past to current and future conditions?





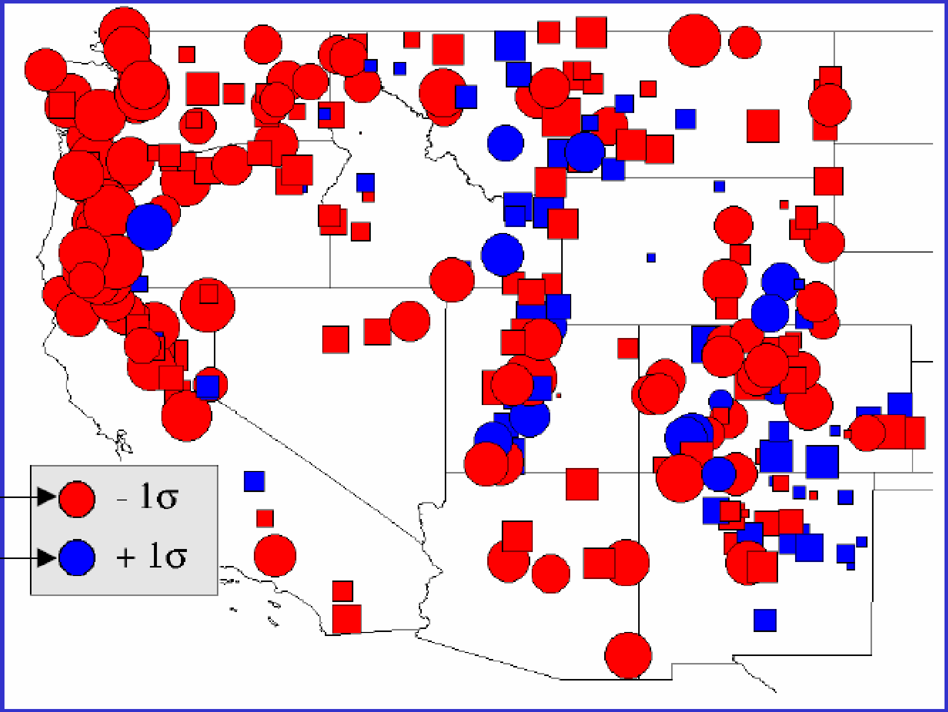
Annual temperatures have risen over the past 110 years, but clear trends in precipitation are not evident

The change in temperature is having an impact on regional snowpack, even without changes in precipitation.

Shift from Snowfall to Rainfall

MORE RAIN, LESS SNOW

LESS RAIN, MORE SNOW



Trends in ratio of winter (Nov-Mar) snowfall water equivalent (SFE) to total winter precipitation (rain *plus* snow) for the period WY1949-2004. Circles represent significant ($p<0.05$) trends, squares represent less significant trends.

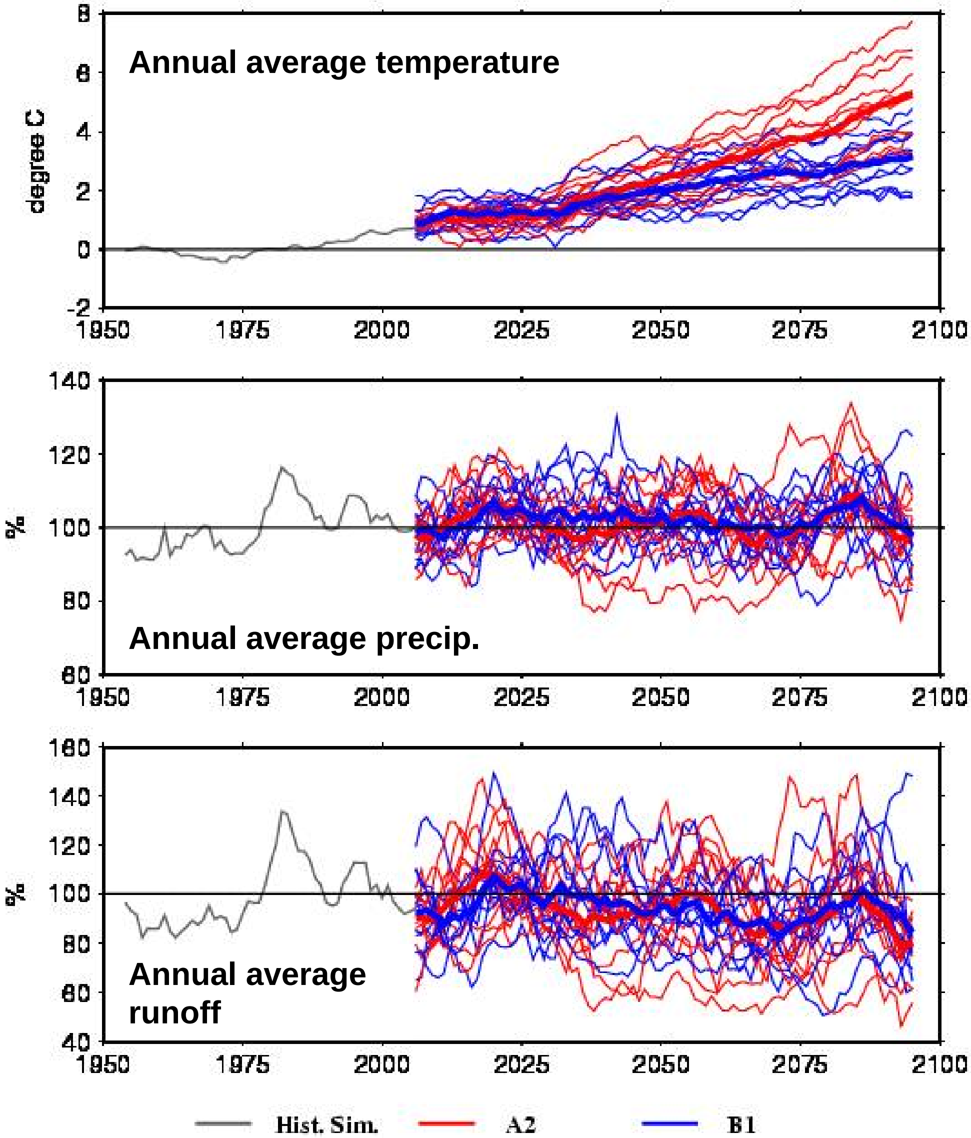
Knowles et al. 2005, AGU

Projections of Future Climate in the upper Colorado River Basin

Observed and projected conditions for the Colorado River Basin above Lees Ferry, using 11 models and 2 scenarios downscaled to the Colorado River basin (upper two panels) and used to drive the VIC macroscale hydrology model (lower panel).

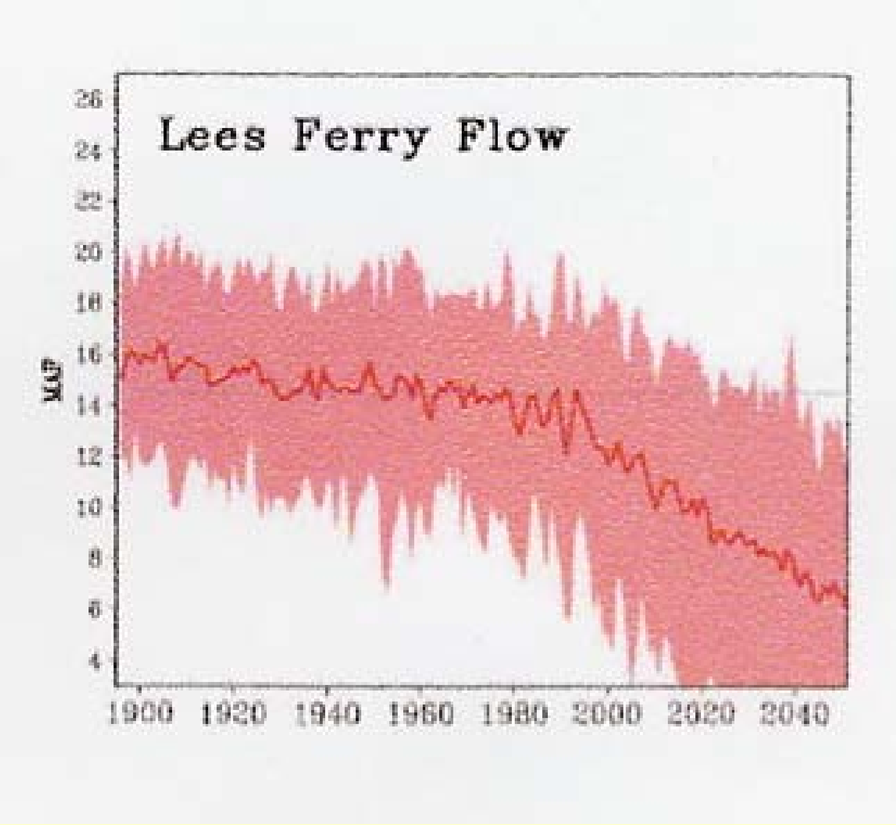
Trends in temperature are obvious, but trends in precipitation and runoff are swamped by variability.

9-year running means expressed as departures from 1950-1999 means



Preliminary data from Christensen and Lettenmaier

Another modeling approach with a different result.



Modeled Lees Ferry annual streamflow, 1895-2050, derived from IPCC 4th Assessment simulations of PDSI. Results from 42 model runs (red line is the average; pink shows the 10%-90% range of individual models). From Hoerling and Eischeid, in prep.

How relevant is the past to planning for climate in the future?

- The climate of the past is unlikely to be replicated in the future, but future scenarios of precipitation do not yet provide useful information for planning and water management
- The range of hydroclimatic variability is projected to increase, however, as demonstrated by model runs
- Centuries-long paleoclimatic records provide a broader range of variability from which to assess the characteristics in the instrumental records
- The variability in the paleohydrologic records may be a useful analogue for future variability
- These long records are needed to assess and understand multidecadal scale variability and its causes

An Example from the City of Boulder

• 4 alternative projected future water demands, (population, households and job changes)

• 3 alternative hypothetical hydrologic scenarios (current, -15%, +25%)

Tree-ring flow reconstructions used as input to water system model, upon which these alternatives were imposed, to test system reliability.

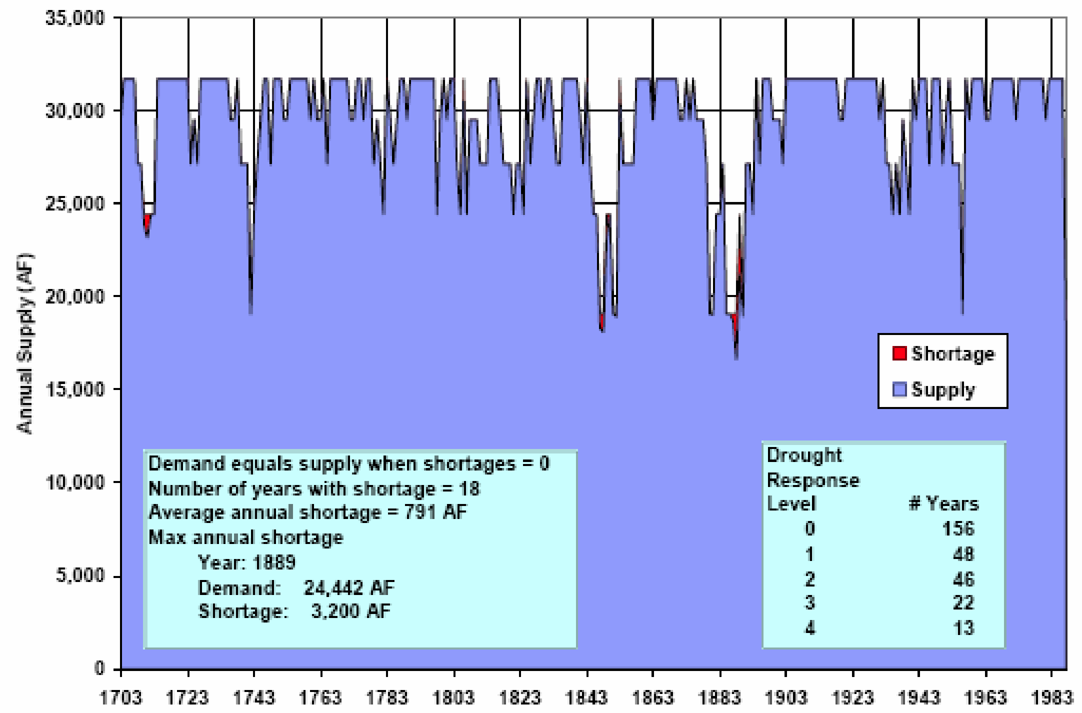


Figure 5. Demands & Supplies: 15% Reduced Flow Hydrology, Current Trends Scenario (demand = 31,700 AF/year).

Table 2: Boulder's Drought Response Triggers and Demand Reductions

Projected Storage Index (1)	Drought Alert Stage	Total Annual Water Use Reduction Goal	Irrigation Season Water Use Reduction Goal
Greater than 0.85	None	0%	0%
Between 0.85 and 0.7	I	8%	10%
Between 0.7 and 0.55	II	14%	20%
Between 0.55 and 0.4	III	22%	30%
Less than 0.4	IV	40%	55%

From Hydrosphere Resource Consultants: Report to the City of Boulder, Sept. 2003

Drought Planning and Paleoclimatology

Gregg Garfin, ISPE, UAZ

Applications to Water Resource Management

and Open Discussion

How are streamflow reconstructions being used by water providers and other decision makers in drought management and planning?

The concept of research-to-operations has become a common theme, but use can cover a broad range of types (Ray 2004)

- Information is ***consulted***; looked up or received in a briefing (awareness)
- After consulted, it is ***considered*** in management (how to use?)
- Some form of the information is ***incorporated*** into operations (modeling challenges)
- Information is used in the ***communication of risk***, and ultimately may play a part in decision making (who makes the decisions and upon what are they based?)

Presentations

Charlie Ester, Salt River Project

Chris Cutler, US Bureau of Reclamation, Upper Colorado River Basin

Bill Girling, Manitoba Hydro

Other Applications

US Bureau of Reclamation - pursuing an analog-type approach, applying the state information (sequences of dry and wet years) from the tree-ring data

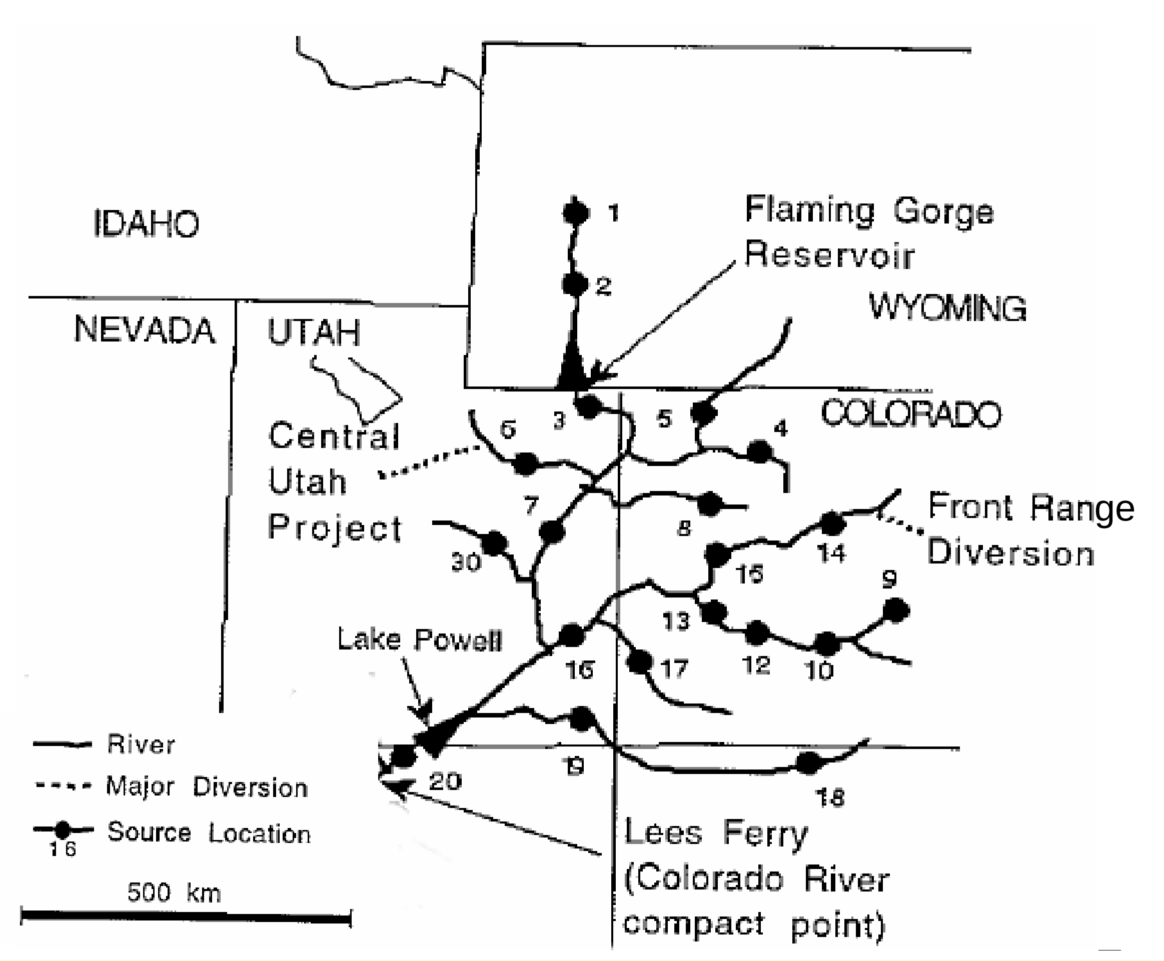
U.S. Bureau of Reclamation uses the Colorado River Simulation System (CRSS) for all long-term operations and planning.

The challenge is to determined the best way to incorporate tree-ring data into the CRSS.

USBR is investigating several approaches, but one is to use the “state” information in the reconstruction to condition and extend the gage record.

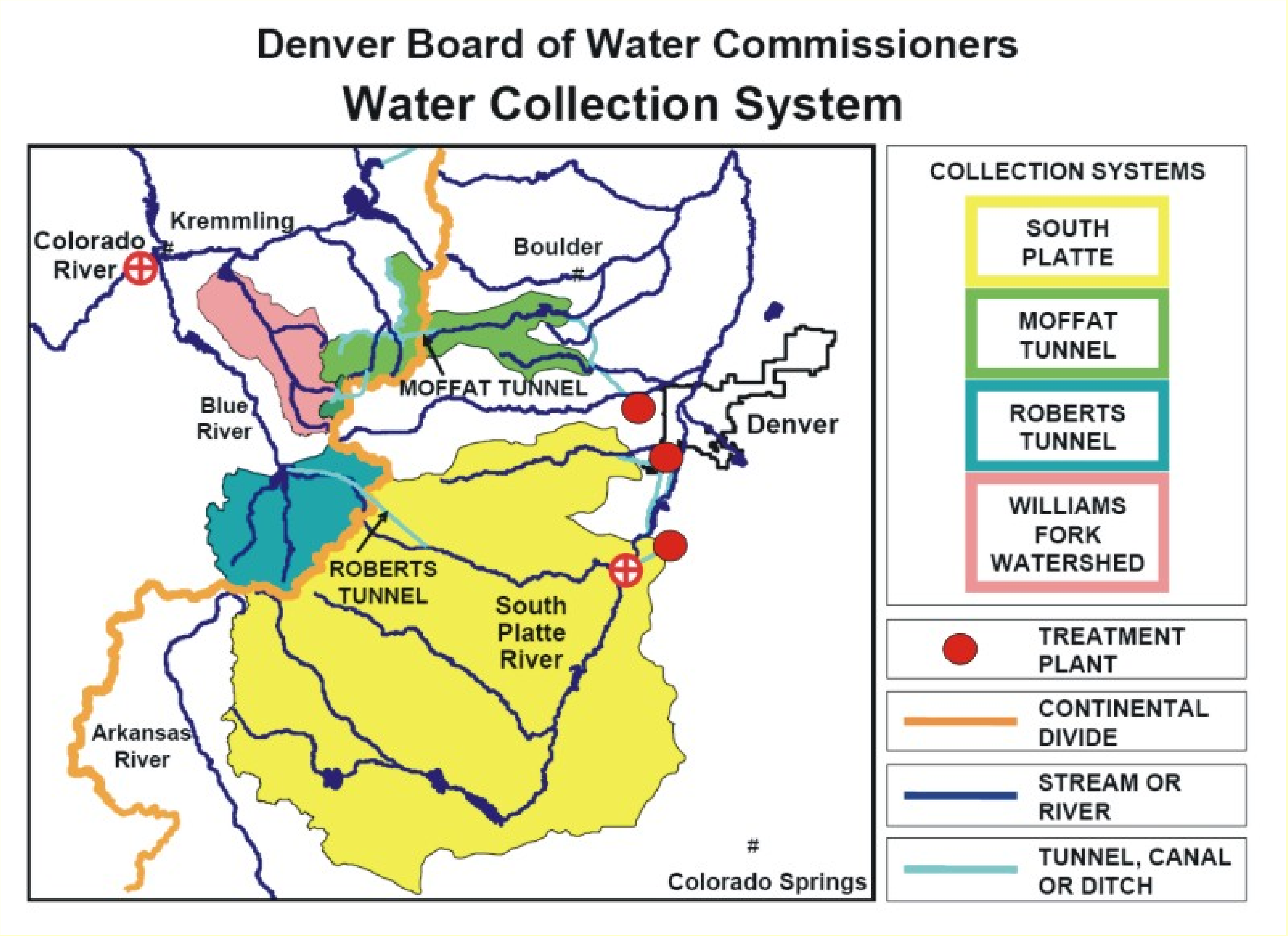
Year	Lees-B	state
1490	22963.22	2
1491	25645.71	2
1492	21008.1	2
1493	19146.06	1
1494	24009.92	2
1495	11285.62	0
1496	5133.229	0
1497	11884.4	0
1498	22286.08	2
1499	13017.14	0
1500	7219.098	0
1501	12520.88	0
1502	14954	0
1503	14149.13	0
1504	17978.97	1
1505	10219.53	0
1506	3955.073	0
1507	13064.56	0
1508	15979.6	1
1509	24389.63	2
1510	16580.49	1
1511	20768.95	2
1512	16906.14	1
1513	19204.67	1
1514	24119.97	2

A “nearest neighbor” approach is used which categorizes both reconstructed and gage values into classes, then selects the “nearest neighbor” analogue year for each year in the reconstruction from the appropriate category in the gage record. The monthly gage values are then used for that year in the reconstruction (this is a bit simplified).



The CRSS model has 19 inputs (these are not gages). The annual reconstructed values for one or a few gages are disaggregated temporally into monthly values (in the conditioning process), and spatially for the 19 locations needed for model input.

Denver Water collection system



Denver Water - use of analog method to disaggregate reconstructed annual flows

Challenge:

How to use annual reconstructed values for a small number of gages in Denver Water system model?

- Platte and Colorado Simulation Model (PACSM)

- An integrated system that simulates streamflows, reservoir operations, and water supplies in the South Platte and Colorado River basins

- Model input is daily data from 450 locations for 1947-1991

Solution:

An “analogue year” approach

- Match each year in the reconstructed flows with one of the 45 model years with known hydrology (e.g., 1655 is matched with 1963), and use that year’s hydrology.

- Years with more extreme wet/dry values are scaled accordingly

- Data are assembled as new sequences of model years

- PACSM is used to simulate the entire tree-ring period, 1650-2002